Fall 2012

A comparison of standard and ventless American lobster trap dynamics

Abigail S. Clark
University of New Hampshire, Durham

A COMPARISON OF STANDARD AND VENTLESS AMERICAN LOBSTER TRAP DYNAMICS

BY

ABIGAIL S. CLARK

B.S., Emmanuel College, 2010

THESIS

Submitted to the University of New Hampshire

in Partial Fulfillment of

the Requirements for the Degree of

Master of Science

in

Zoology

September, 2012

This thesis has been examined and approved.

Thesis Director, Dr. Winsor H. Watson, III

Professor of Zoology

Dr. W. Huntting Howell

Professor of Zoology

Dr. Steven H. Jury

Senior Research Scientist

University of New England, Biddeford, Maine

8/1/12

Date

DEDICATION

This thesis is dedicated to my family and friends for their unending love and support during pursuit of my goals. I am truly blessed to have them in my life.

ACKNOWLEDGEMENTS

I would like to thank my advisor and thesis director, Dr. Win Watson, for welcoming me into his laboratory. Working with Win has been an honor and blessing. His expertise, skills, and love of learning are among the many qualities that I admire in him. Having been given the opportunity to work with Win has been a truly rewarding and unforgettable experience.

I am also very thankful for my committee members, Drs. Steve Jury and Hunt Howell. I have had the pleasure of working with both throughout my graduate career. Steve, thank you for enhancing my knowledge base with your intellect and thought-provoking ideas. Many thanks to you, Hunt, for educating me on fisheries management and for helping me to fully understand the relevancy of my work. Your contributions to this project and to my development as a scientist are deeply appreciated.

My gratitude extends to the team of professionals who assisted me throughout this entire process. I would thank the Watson Lab for its continued guidance and support. Much appreciation goes specifically to Jason Goldstein, Tom Langley, Beth Dubofsky, Tracy Pugh, and Helen Cheng. I would also like to thank the Watson Lab interns, especially Kyle Jenks, Liz Morrissey, and Chris Chambers, for helping me during different stages of this project. Many thanks to Carl Wilson for providing insight and perspective to this study and its implications. I would like to recognize the following UNH personnel and affiliates as well for helping me with various aspects of my graduate career: Liz Kintzing, Dave Shay, Nate Rennels, Noel Carlson, Nancy Wallingford, Diane Lavalliere, Charlotte Cooper, Michelle Scott (Professor Emerita), James Taylor, Ed O'Brien, Jessica Bolker, Larry Harris, and my UNH peers. You were all instrumental in making my time at UNH a very pleasant and memorable experience. I would like to express my appreciation for the UNH Graduate School and Department of Biological Sciences for providing me opportunities to teach and to work with many wonderful students, to whom I am also grateful.

Finally, my gratitude goes out to my family. Mom and Dad, you recognized my passion for marine science at a very early age. Thank you for fostering my love of the ocean. Sarah and Nathaniel, thank you for always exploring intertidal pools with me (and ensuring that I didn't fall in them). To Brian, words cannot express my appreciation. From the late night writing to the early morning data crunches, you supported me wholeheartedly. Thank you.

This project was supported by the N.H. Sea Grant Program without which this study would not have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

CHAPTER II

LIST OF TABLES

ABSTRACT

A COMPARISON OF STANDARD AND VENTLESS AMERICAN LOBSTER TRAP DYNAMICS

BY

Abigail S. Clark

University of New Hampshire, September, 2012

The American lobster, *Homarus americanus*, is the most valuable marine resource in New England and, as with any fishery, effective management depends on accurate stock assessment. The purpose of this study was to examine the efficacy of standard and ventless traps, focusing on determining which trap provides a better index of lobster abundance. While ventless traps caught approximately five times as many lobsters as standard traps, the size of captured lobsters did not differ significantly between trap types. Ventless traps saturated after 16 - 24 hours, but standard traps did not saturate at all. Despite saturating at all densities, ventless traps yielded higher catch at higher densities, so their maximum catch correlated with lobster abundance. Time-lapse videos suggest that ventless traps saturate due to a reduction in entries since there are fewer surrounding lobsters. This study indicates that ventless traps provide more useful information about lobster populations than standard traps.

INTRODUCTION

Fisheries Management

The American lobster, *Homarus americanus* (H. Milne-Edwards, 1837), is the most important fishery in northeastern North America, with Maine landings alone valued at $331 million (Maine Department of Marine Resources, DMR, 2012a). For management purposes, the Atlantic States Marine Fisheries Commission (ASMFC) has divided the American lobster fishery into three stock areas: Gulf of Maine, Georges Bank, and Southern New England. Southern New England has experienced significant declines since the 1990s (DMR, 2012b). Therefore, extensive efforts have recently been made to better monitor this fishery (DMR, 2011).

Two major acts have been instituted to help sustain and replenish the American lobster fishery: 1) the ASMFC Interstate Fishery Management Plan for American Lobsters and; 2) the Atlantic Coastal Fisheries Cooperative Management Act (ASMFC, 2012b; NOAA Fisheries Service: Sustainable Fisheries Division, 2012). The ASMFC Interstate Fishery Management Plan for American Lobsters enforces the following regulations, among others, in state waters: size limits on harvestable lobsters, gear restrictions, limits on the number of allowable traps, and mandatory reporting of catch (ASMFC, 2012a). Federal waters are monitored by the Atlantic Coastal Fisheries Cooperative Management Act, which imposes regulations similar to those of state waters (NOAA Fisheries Service: Sustainable Fisheries Division, 2012; NOAA FishWatch, 2012).

Various methods are used to estimate American lobster abundance. Dive surveys are an effective technique for characterizing lobster populations on a local scale, primarily for research purposes (Jury *et al*., 2001; Steneck & Wilson, 2001; Tremblay *et al.*, 2006). However, while very accurate, dive surveys are impractical to employ throughout the three management stocks because they are time consuming, expensive, have depth limitations, and cover only a small fraction of the bottom in a given area.

Annual trawl surveys, on the other hand, are advantageous in that they can sample large areas. A disadvantage to such surveys is that their sampling stations are mainly based offshore to avoid gear conflict in inshore waters and untrawlable bottom (Chen *et al.*, 2006). When inshore trawl surveys are conducted, managers must request that fishers remove all fixed gear (i.e. lobster traps, gillnets, etc.) from the survey site. Aside from potential gear conflicts, trawl surveys are not generally performed in rocky, complex habitats, where many lobsters reside.

In Canada, fishery-dependent sampling is an alternative approach used to assess lobster abundance. Two major fishery-dependent sampling programs have been initiated, port sampling and sea sampling. Port sampling provides data solely on the catch of marketable lobsters and the amount of effort required to catch them. Unlike port sampling, sea sampling collects information on both the quantity and size frequency composition of catch. These additional data about sublegal lobsters are very useful and can, for example, be used to model and predict the number of lobsters to be recruited into the fishery in subsequent years. Recently, managers have started to focus more on sea sampling, particularly since there is a strong correlation between port sampling and sea sampling catch (Scheirer *et al.*, 2004).

CPUE data from standard lobster traps currently serves as the easiest, most cost-effective method for approximating lobster abundance and size frequency composition. However, there are several shortcomings associated with this method. For example, Jury *et al.* (2001) discovered that only 6% of the lobsters that enter standard lobster traps are ultimately captured, while the remaining 94% escape. This suggests that the number of lobsters caught by standard lobster traps may not accurately reflect the number and sizes of lobsters on the bottom. In order to compensate for the inefficiency of these standard traps, organizations such as the Maine DMR and the Massachusetts Division of Marine Fisheries (MADMF) conduct ventless trap surveys to better assess the relative abundance and size composition of lobsters (MADMF, 2009; DMR, 2011). Ventless traps, unlike standard traps, lack escape vents that traditionally allow sublegal lobsters to escape (Estrella & Glenn, 2006). Because of their ability to retain sublegal lobsters, ventless trap surveys should provide more insight into the relative abundance and size composition of lobsters in the area of interest.

Lobster Catchability

There are many factors that influence the "catchability" of lobsters and several studies have demonstrated how the behavioral interactions between lobsters appear to influence the characteristics and quantities of lobsters captured in traps. For example, the catchability of lobsters may depend on the size and density of lobsters within a particular area (Tremblay *et al.*, 1998). More specifically, it has been proposed that agonistic interactions between lobsters in and around traps discourage other lobsters from entering the traps (Richards *et al.*, 1983; Karnofsky & Price, 1989; Jury *et al.*, 2001; Tremblay *et* *al.*, 2006). Reduced catch due to agonistic behavior was also observed in Dungeness crabs, where outside crabs "guard" pot entrances and thus prevent other crabs from entering (Barber & Cobb, 2009).

Catchability is also influenced by the sex of lobsters within the effective fishing area (EFA), as observed by Miller (1995). Male and female lobsters between 60 and 69 mm exhibited similar catchabilities, but this changed with increasing size. For lobsters with 70-109 mm CL, female catchability decreased and male catchability increased. Higher catchabilities in male American lobsters have also been documented in other studies (Tremblay *et al.*, 2006; Courchene & Stokesbury, 2011).

Lobster catchability is not only a function of sex, but of habitat and catch size as well. Lobsters are attracted to highly complex, heterogeneous substrates (Geraldi *et al.*, 2009; Courchene & Stokesbury, 2011). In such areas, shelter and protection from predation are available and can accommodate high densities of lobsters (Richards & Cobb, 1986; Wahle & Steneck, 1992). Because lobsters compete for shelter and can prevent one another from entering traps, it is expected that aggressive interactions increase with increased substrate complexity, thus, initially decreasing catchability (O'Neill & Cobb, 1979; Richards *et al.*, 1983). If, for example, a large lobster is present inside the trap, the lobster can deter smaller lobsters from entering (Richards *et al*, 1983; Frusher & Hoenig, 2001; Jury *et al.* 2001). Throughout the fishing season, however, large lobsters are trapped and harvested thus potentially increasing the catchability of smaller lobsters over time (Frusher & Hoenig, 2001; Tremblay & Smith, 2001; Ihde *et al.*, 2006). While standard trap dynamics have been investigated extensively, very few studies have assessed ventless trap dynamics.

Only a handful of studies have evaluated the performance of ventless traps. Courchene and Stokesbury (2011) explored this subject by fishing ventless and standard traps off of Buzzards Bay, Massachusetts for soak times of 72-120 hours. Total catch, size frequency distributions, and the sex of captured lobsters were quantified and then compared to data from corresponding dive surveys. Comparing the catch data to SCUBA data under these conditions demonstrated that catch in ventless trap surveys overestimated the average size of lobsters and the frequency of males in the population. In another study assessing catch in ventless traps, standard (vented) traps reflected juvenile lobster abundance better than ventless traps. By fishing both trap types along the coast of Maine for 3-14 days, Poeschel (2002) found that there was a strong relationship between landings and sublegal lobsters captured in standard traps. In both ventless trap studies, traps were fished for at least three days. It is, therefore, possible that trap saturation might have influenced their data.

Gear Saturation

It is widely accepted that trap saturation is a common occurrence in fisheries. While trap saturation is prevalent, its properties are not well understood. Trap saturation, as defined by Miller (1979), is a decrease in catch rate with increasing catch. Munro (1974), however, proposed that traps saturate when catch rate balances a percentage of animals escaping. In both cases, catch was asymptotic with soak time and leveled off at a maximum catch value. Auster (1985) demonstrated the asymptotic nature of American lobster catch over time. He also showed that, after traps saturate, catch values begin to decline. Studies based on these findings suggest that trap saturation is the point at which maximum catch is achieved (Auster, 1986; Fogarty & Addison, 1997). In the present study, we defined trap saturation as there being no significant increase in catch over soak time.

Trap saturation is influenced by a suite of factors such as behavioral interactions, trap design, and soak time (Miller, 1990; Miller & Rodger, 1996; Jury *et al.*, 2001). Saturation in commercial traps has been the subject of many studies, as CPUE serves as a relative abundance index and, if traps saturate, then CPUE could underestimate lobster abundance. In one of the first studies addressing trap saturation, the "saturation effect" was observed in squirrelfish and sablefish pots when entry rate decreased as soak time increased (High & Beardsley, 1970). Gear saturation was later documented among Atlantic cod pots (Ovegard *et al.*, 2011). In a study involving the American lobster, Miller and Rodger (1996) showed that standard lobster traps tended to saturate within 12 hours of being deployed.

There are a number of mechanisms that might be responsible for lobster trap saturation including: decay or disappearance of bait, removal of all the animals in the area fished, high rates of escape and competition between lobsters in and around a trap. Bait plume dynamics and bait quality may influence when a trap saturates. The area of bait attraction for lobsters is approximately 11 meters from the odor source (Watson *et al*, 2009), so lobsters within this radius are likely to be drawn to the bait. When bait is placed inside a trap, lobsters begin to approach almost immediately (Jury *et al.*, 2001). As bait is removed by feeding lobsters and other species the rate at which amino acids are released from the bait is reduced (Mackie *et al.*, 1980; Lokkeborg, 1990). With slowed chemical release, catch rate of lobsters might also be lowered. While bait may be one factor affecting trap saturation, it is quite possible that the effective fishing area (EFA) is another factor. The EFA surrounding the trap of interest may be fished so much that there are no more lobsters in the immediate vicinity to be captured and, hence, the trap saturates. Trap saturation may also be a function of behavioral interactions, as Barber and Cobb (2009) demonstrated. They showed that agonistic behavior in Dungeness crabs prevented other crabs from entering the pot. Similar observations were made regarding lobster territoriality of traps in that large lobsters reduced the entry rate of smaller lobsters over time (Richards *et al.*, 1983; Jury *et al.*, 2001; Watson & Jury, in press).

Overview of Thesis

In Chapter One, data are presented from a series of trials in which standard and ventless traps were fished at the same time and in the same location for a range of soak times. Catch in both trap types were then compared to true (estimated to the best of our ability by SCUBA surveys) lobster abundances and size frequency compositions on the bottom of the study site. We hypothesized that ventless traps would provide the best index of abundance and population structure, as compared to standard traps since ventless traps retain more sublegal-sized lobsters. Another objective of the experiments outlined in Chapter One was to determine at which soak times ventless and standard traps saturate. I tested the hypothesis that ventless traps would saturate faster because lobsters cannot escape and thus, as they accumulated in the trap they would prevent other lobsters from entering. I also kept track of the amount of bait remaining in the bait bags over time to test the hypothesis that bait disappearance was a factor contributing to trap saturation. In Chapter Two, I present the results from a series of studies in which an underwater camera was mounted on top of standard and ventless traps to record lobster behaviors in and around each type of trap. Lobster interactions were compared between the two types of traps to determine what factors might cause the traps to saturate. I was most interested in determining if agonistic interactions between lobsters contributed to trap saturation.

CHAPTER 1

THE RELATIONSHIP BETWEEN STANDARD AND VENTLESS TRAP CATCH AND THE SIZE STRUCTURE AND ABUNDANCE OF LOBSTERS

Abstract

Recently, ventless trap surveys have become more common for lobster population monitoring. These surveys are important for tracking trends in the fishery and gathering data about the size structure of local lobster populations. The purpose of this study was to conduct ventless and standard trap surveys in parallel with SCUBA surveys in order to determine how catch in both types of traps relates to the lobster population on the bottom. In addition, because trap saturation may impact the final catch, we quantified how catch changed over time by pulling traps after soak times of: 2, 4, 6, 8, 10, 16, 24, 48, 72, and 96 hours. All surveys were carried out between June and October of 2010 and 2011, at a study site just off the coast of Rye, NH. During each month ventless traps captured approximately five times as many lobsters as standard traps, but the size of the lobsters captured did not differ between the trap types. Standard traps never really saturated because catch was constant throughout each trial. Ventless traps, however, saturated between 16 and 24 hours. Traps saturated at all lobster densities, but had higher final catch values during higher densities. As a result, there was a fair to good relationship between lobster density and ventless trap catch after 16 hours ($r^2 = 0.4075$), 24 hours ($r^2 = 0.4312$) and 48 hours ($r^2 = 0.6578$). Bait loss did not appear to be a factor in trap saturation because standard trap catch did not change over time, even though bait slowly disappeared. Ventless

traps had approximately 50% of bait remaining after 24 hours, and yet the traps were already saturated at this point. These data indicate that ventless traps do, in fact, provide much more useful information about natural lobster populations than standard traps. Ventless traps should, therefore, be considered as useful tools for collecting data to use in the assessment of this valuable fishery.

Introduction

Sustaining fisheries is a challenge faced by managers worldwide. Management of the American lobster, *Homarus americanus* (H. Milne-Edwards, 1837), fishery is no exception. The American lobster fishery accounts for 78% of all Maine landings (ex-vessel, in terms of value), and is an important fishery in many Atlantic coastal communities (Maine Department of Marine Resources, DMR, 2012a). Therefore, managing this fishery and mitigating the pressures of overfishing are of utmost concern to the longevity of the American lobster industry.

State and federal governments have established programs that may reduce overexploitation of lobsters. For example, the Interstate Fishery Management Plan for American Lobsters and the Atlantic Coastal Fisheries Cooperative Management Act help to monitor and regulate the lobster fishery (Atlantic States Marine Fisheries Commission, ASMFC, 2012a; NOAA Fisheries Service: Sustainable Fisheries Division, 2012). Supplemental sampling programs have also been established to examine the effectiveness of the aforementioned bylaws and to track the state of the fishery.

Fishery-independent and fishery-dependent sampling programs are used by managers to measure lobster abundance and spatial distribution. Beginning in the 1960s, the National Marine Fisheries Service (NMFS) has performed fishery-independent trawl surveys. However, this sampling method is generally restricted to depths greater than 50 meters and is, therefore, not always practical for stock assessment of lobsters residing in shallow inshore waters (Chen *et al.*, 2006). While inshore trawl surveys have been performed throughout the years, there are several issues stemming from gear conflict that make this technique a challenging one to implement (NH Fish and Game, 2012). Information regarding inshore stocks is thus primarily derived from fishery-dependent sampling data, such as those collected via port and sea sampling methods (DMR, 2001; Scheirer *et al.*, 2004). Lobstermen, however, fish traps in areas where the densities of legal-sized lobsters are relatively high. Data collected in these locations may, consequently, overestimate abundance of large inshore lobsters. Moreover, standard traps are size selective, so small lobsters are underestimated. To supplement these and other sampling techniques, the DMR and Massachusetts Division of Marine Fisheries (MADMF) have instituted ventless trap surveys (Scheirer *et al.*, 2004; MADMF, 2009; DMR, 2011).

Ventlesss traps and commercially used standard traps are similar in structure. Each consists of two compartments, a kitchen and a parlor. The two traps differ in that standard traps are designed to allow sublegal-sized lobsters to escape, while retaining anything above the minimum legal limit of 83 mm in carapace length (CL). In a study assessing lobster-trap interactions, Jury *et al.* (2001) found that only 6% of the lobsters entering standard traps are captured. Of the remaining 94%, 28% exited through the escape vent and 72% through the kitchen entrance. Standard trap catch-per-unit-effort (CPUE), therefore, only weakly correlates with estimated lobster abundance (Watson & Jury, in press). Biologists have supplemented trawl survey data with ventless trap surveys in order to better assess lobster population structures. Ventless traps, unlike standard traps, do not have escape vents that would otherwise permit small lobsters to leave the parlor (Estrella & Glenn, 2006).

While ventless trap surveys are widely used in coastal New England States, very few studies have analyzed the dynamics of ventless traps and the relationship between ventless trap catch and lobster abundance. Courchene and Stokesbury (2011) performed a study comparing ventless trap catch to the size frequency distribution and abundance of the lobster population in the same area fished by the traps. Ventless traps that were fished for 72-120 hours captured a larger size distribution and more male skewed sex ratio than SCUBA surveys. This study also provided insight into the effect that habitat and temperature have on ventless trap catch. Ventless CPUE increased with substrate complexity and when water temperature was relatively constant, but decreased with rising temperatures. In addition to temperature and bottom type, trap saturation may have caused a reduction in trap catch, but as the authors suggest, future studies are required to confirm this.

One of the factors that can lead to discrepancies between the actual lobster abundance and catch in traps is "trap saturation". Trap saturation, a phenomenon responsible for reducing catch or keeping it constant over time, appears to be a function of multiple factors (Miller, 1990; Barber & Cobb, 2009). It has been investigated in a variety of fisheries, ranging from the Dungeness crabs to Atlantic cod, but much remains unknown (Miller, 1979; Ovegard *et al.*, 2011). One cause for reduced catch is believed to be behavioral interactions among species congregating in and/or around traps (Addison & Bannister, 1998). Pre-stocking studies have shown that tethering lobsters inside traps reduce catch within a 24-hour soak period (Richards *et al.*, 1983; Addison, 1995). In a study conducted by Barber and Cobb (2009), Dungeness crab territoriality and aggression discouraged other crabs from entering the pot. Similar behavior has been observed in other studies, where large lobsters tended to prevent smaller lobsters trying to enter traps, thus limiting entries (Jury *et al.*, 2001; Watson & Jury, in press). Saturation has also been observed among fish pots, where Atlantic cod entry rate decreased with increased catch (Ovegard *et al.*, 2011). This same "saturation effect" was also documented for squirrelfish and sablefish (High & Beardsley, 1970).

While behavioral interactions are most widely accepted as a cause for trap saturation, there are several other valid hypotheses. For example, some argue that saturation occurs when gear accumulates so much catch that there is not enough space to capture more (Prchalová *et al.*, 2011). Loss of bait is also thought to influence when traps saturate. Given the fact that ventless traps typically capture more animals than standard traps, one might assume that the traps would also fill up faster, lose bait quicker, and saturate faster than standard traps, which are thought to saturate in less than 24 hours. Since a typical ventless trap survey lasts for 72 hours, it is important that researchers evaluate ventless trap dynamics in order to better understand if trap saturation might be skewing the results obtained (DMR, 2011).

In the present study, standard and ventless trap saturation was investigated during 2010 and 2011. Standard and ventless traps were fished in pairs off the coast of New Hampshire for the following time soak times: 2, 4, 6, 8, 10, 16, 24, 48, 72, and 96 hours. Catch quantity and size composition were then compared to the estimated lobster population, as determined by dive surveys. I also measured the amount of bait remaining in bait bags after different soak times to test the hypothesis that bait disappearance contributed to trap saturation. As expected, I found that ventless traps captured more lobsters and provided a better index of the density of lobsters in the study area.

Surprisingly, the data obtained suggest that saturation in ventless taps might be due to the removal of the vast majority of lobsters within the effective fishing area of the traps.

Materials and Methods

Study site

All data were collected in waters ranging from 7-10 meters deep, from May through October of 2010 and 2011, near Wallis Sands State Beach in Rye, NH. In this location of approximately 90,000 m^2, the bottom primarily consists of sand, which made it easy to visualize lobsters both during SCUBA surveys and in video recordings (Fig. 1.1). The area was also void of active lobstermen, and it was the site for similar past investigations (Jury *et al.*, 2001; Watson & Jury, in press).

Figure 1.1. Photo illustrating the sandy, homogenous characteristics of study site off the coast of Wallis Sands State Beach. In photo, lobsters are shown along transect tape.

Another valuable feature of this site was that the density of lobsters changes seasonally (Fig. 1.4). Much of the variation in lobster density was probably related to seasonal shifts in water temperature since lobsters tend to behaviorally thermoregulate, preferring areas with water temperatures around 16°C (Crossin *et al.*, 1998). Fluctuations in water temperature, and thus lobster densities, made it possible to determine how entry rate into traps and CPUE varied with lobster density.

During the study, the bottom temperature at this site was monitored using HOBO data loggers (Onset, Inc., United States) that were programmed to log data every 30 minutes from May through October of 2010 and 2011 (Fig. 1.4). The temperature loggers were attached to traps fished at the study site. Note that temperature data for some dates (9/2/10-9/8/10, 9/22/10-10/3/10) were unavailable for the Wallis Sands area, due to storms, so temperature data collected 6.02 km away at the University of New Hampshire Coastal Marine Laboratory were used for these days instead.

SCUBA surveys

A total of 20 SCUBA surveys were conducted in 2010 and 2011 (8 and 12, respectively). SCUBA surveys were carried out a week before and/or after fishing traps. Two different types of surveys were performed during the duration of the field season; one involved the collection of lobsters so that their sex and size could be determined, and the other was used solely for quantifying the density of lobsters. In order to assess the size frequency composition of lobsters on the bottom, divers collected lobsters along transects that were 30-60 meters long and from 4 to 6 meters wide, depending on visibility. Two SCUBA divers, one on each side of the transect tape, swam a total of four transects per lobster survey. After surveying the area, all lobsters were pooled together and brought to the surface where their CL, abdomen widths (ABW), and gender were determined. Lobsters were then released at the site of capture within 20 minutes of being collected. To measure lobster abundance, two SCUBA divers swam four transects similar to those previously described. Instead of collecting lobsters, however, lobsters were strictly counted along transects. In general, abundance surveys were conducted prior to fishing traps to avoid handling lobsters and potentially causing them to move out of the area, while the other surveys were carried out after traps were fished.

Traps

Twenty-one pairs of ventless and standard traps, provided by MADMF, were deployed a total of 372 times at the study site, from May through October of each year (Fig. 1.2). Traps were deployed in trawls parallel to shore with each standard trap being deployed before its ventless counterpart. Pairs of traps were always set 50-100 meters apart from each other. Every trap pair was labeled and returned to the same location for the duration of the study (Fig. 1.3). During each trial, traps were hauled in a random sequence.

Standard traps were similar in design to the single parlor traps used in the fishery, but they were made with 1 x 1 inch wire mesh, rather than the 1.5 x 1.5 mesh that is used for commercial traps. Each rectangular trap used in this study was 90 cm x 47 cm x 35 cm and had two main compartments, a kitchen and parlor. The kitchen, which contained the bait and entrance heads, was connected to the parlor via a mesh funnel that allowed lobsters to move from the kitchen to parlor. Inside the parlor, escape vents (14.6 cm x 4.9 cm) were used to allow sublegal-sized lobsters (CL $\leq$ 83 mm) to exit the trap (Estrella & Glenn, 2006). Unlike standard traps, ventless traps lacked escape vents. Other than the absence of escape vents, standard and ventless traps were identical.

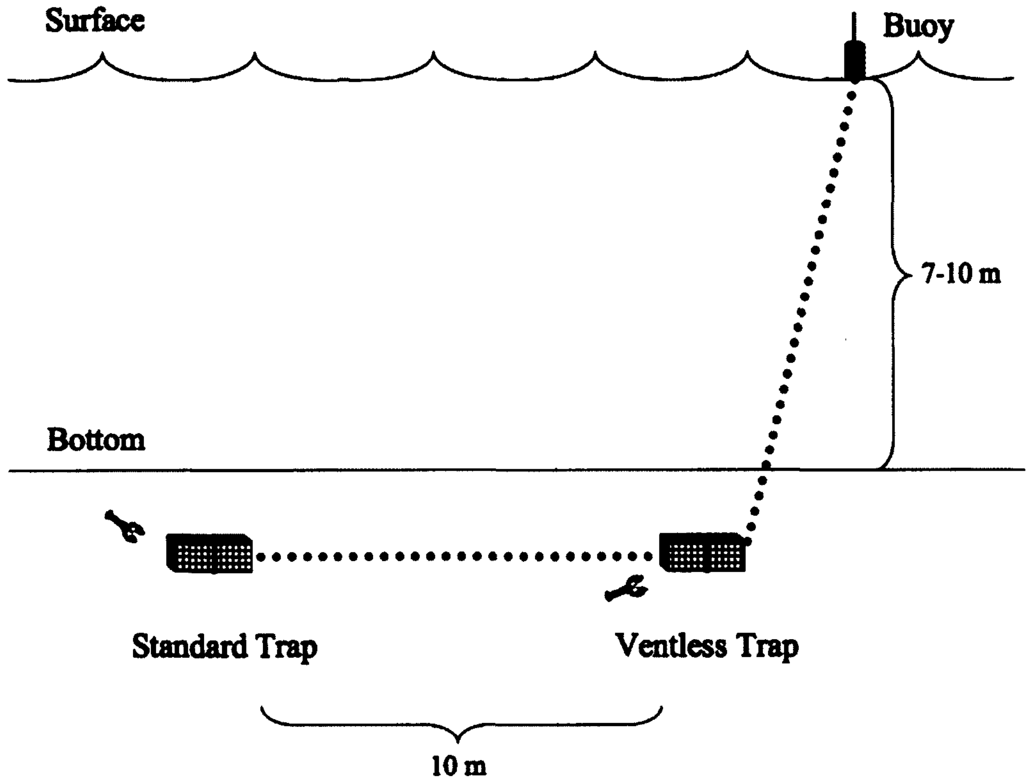

Figure 1.2. Schematic of deployed trap pair. Each ventless trap (n = 21) was attached to a standard trap and fished for soak times ranging from 2 to 96 hours. Paired standard and ventless traps were connected by a 10-meter groundline.

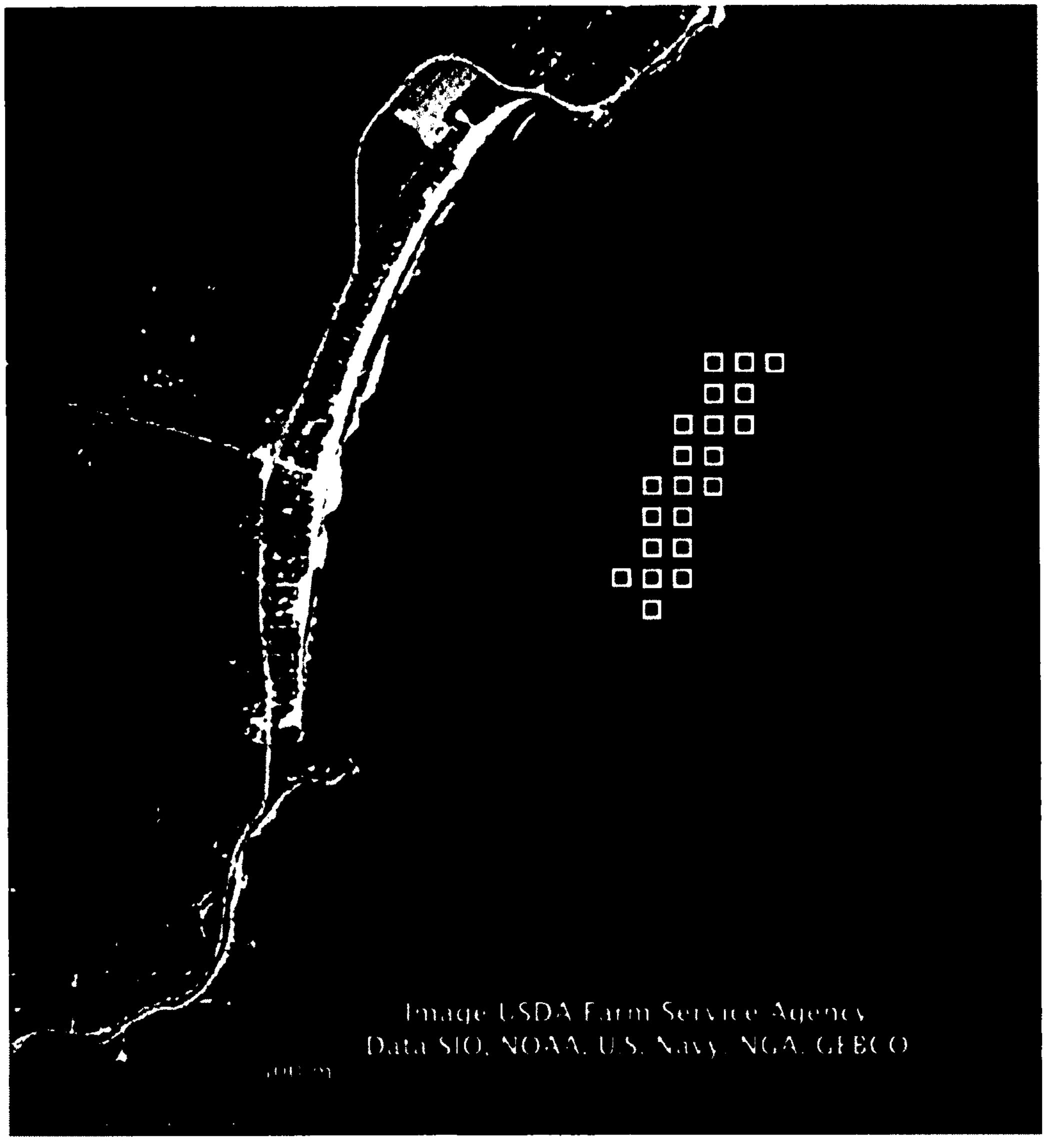

Figure 1.3. Map of study site, off the coast of Wallis Sands State Beach. Each square represents location of trap pair (n = 21). Modified image courtesy of Google earth.

Experimental protocol

Approximately every two weeks, groups of three randomly selected pairs were baited and fished for the following soak times: 2, 4, 8 (or 6), 10 (or 16), 24, 48, 72, and 96 hours. This protocol yielded n=3 for each trap type, for each time period, for each trial. These three trap pairs per time period were treated at replicates. A total of 12 saturation trials were completed between 2010 and 2011 (Table 1.1) and these trials were matched with SCUBA surveys that took place during the same time period. For example, Trial 3 of 2011 spanned two months-June and July. Therefore, the average lobster density for Trial 3 included data from the end of June and the beginning of July. All traps in each trial were baited with three (≥ 0.2 kg in total) Atlantic herring. During 2011, the amount of bait remaining in each trap was estimated and compared to the original starting amount of bait, when traps were hauled.

2010 Trial #	Start Date	End Date	Lobster Density	# Trap Pairs Fished
1	6/4/10	6/28/10	0.03 ± 0.005	29
2	7/6/10	7/9/10	0.033 ± 0.008	24
3	8/2/10	8/22/10	0.056	30
4	8/30/10	9/27/10	0.16 ± 0.004	22
5	10/8/10	10/20/10	0.001	22
2011 Trial #	**Start Date**	**End Date**	**Lobster Density**	**# Trap Pairs Fished**
1	5/31/11	6/13/11	0.024 ± 0.007	24
2	6/17/11	6/27/11	0.094	24
3	6/28/11	7/12/11	0.053 ± 0.009	32
4	7/19/11	7/29/11	0.01	34
5	8/5/11	8/26/11	0.11 ± 0.028	37
6	8/30/11	9/23/11	0.068 ± 0.015	40
7	9/23/11	10/31/11	0.011 ± 0.007	54

Table 1.1. Summary of standard vs. ventless trap trials. Trials took place from June through October in both years. Note that lobster density is presented in # of lobsters/m^2 (± SEM).

Data analyses

The overall objective of this study was to determine the relationship between trap catch and lobster abundance. To first evaluate the number of lobsters captured in ventless traps and standard traps, mean CPUE for each trap type, in each month, was first transformed by calculating the natural log of all CPUE. Transforming the CPUE data prior to analyzing them satisfied normality assumptions. A student's *t*-test was then used to compare the log-transformed CPUE data of standard traps to those of ventless traps.

Ventless trap CPUE was further evaluated using saturation curves. After plotting CPUE over soak time, logarithmic regression analyses were performed to determine if a relationship existed between the ventless trap CPUE and the estimated lobster abundance. Similar analyses were completed for ventless trap CPUE collected at different lobsters densities to determine if lower densities yielded a stronger logarithmic fit with CPUE than higher densities. Segmented linear regression analyses were then used to detect the point at which lobster entry rate in ventless traps decreased with increased soak time.

The relationship between lobster density and ventless trap catch was assessed by plotting 2010 and 2011 values for the following time trials: 2, 4, 16, 24, 48, and 72 hours. Linear regression analyses were used to determine which of these six soak times produced the best correlation between ventless trap CPUE and lobster density

In 2011, bait loss in standard and ventless traps was investigated to determine if it might change significantly with immersion time. Bait quantities were visually estimated before and after fishing trap pairs. The percent of bait remaining in each trap type was compared across soak times (2-96 hours) and months during which the study was conducted (June-October). One-way ANOVAs, followed by Tukey's Multiple Comparison Test, were used to detect any significant differences between bait consumption and trap types.

Results

Seasonal fluctuations in water temperature and lobster density

The water temperature at the study site fluctuated in a seasonal manner, ranging from daily averages of 8.62 ± 0.05°C in June to 18.64 ± 0.38°C in September of 2010 and from 7.16 ± 0.04°C in June to 19.66 ± 0.64°C in August of 2011 (Fig. 1.4A).

The density of lobsters at the study site, as determined by SCUBA surveys, ranged from 0.001 lobsters/m^2 to a peak of 0.16 ± 0.004 lobsters/m^2 in (Fig. 1.4B). The means for 2010 and 2011 respectively were 0.051 ± 0.012 lobsters/m^2 and 0.053 ± 0.008 lobsters/m^2 respectively. All variations in this manuscript are reported as standard error of the mean (SEM).

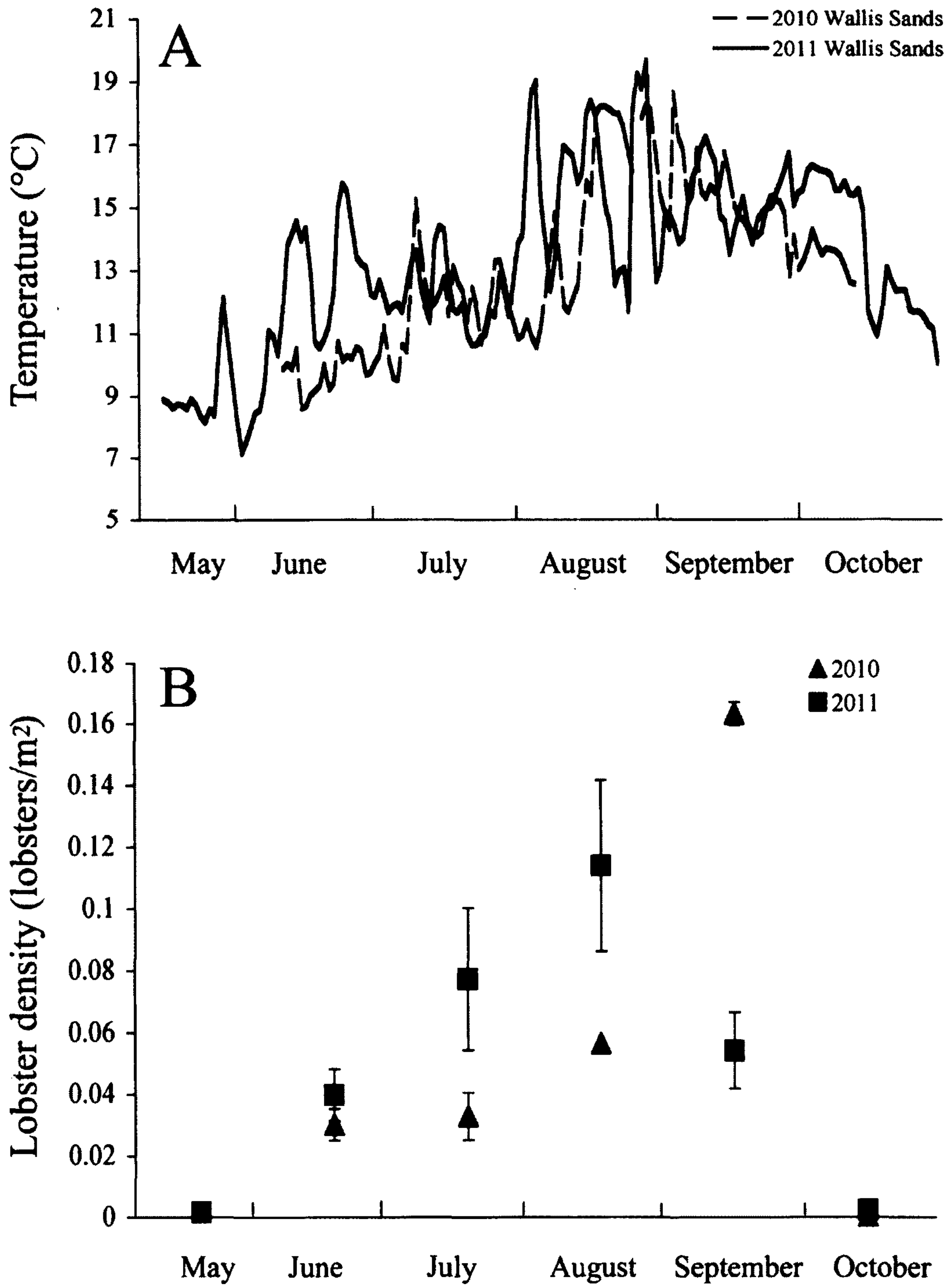

Figure 1.4. A) Temperature and B) lobster density (lobsters/m^2) at the study site located just offshore of Wallis Sands State Beach. Temperature (A) was recorded every 30 minutes and averaged for each day, while lobster abundance (B) was determined by SCUBA surveys biweekly. Both temperature and lobster density data were collected between May and October of 2010 and 2011.

Comparison of gear selectivity based on size composition of catch

A total of 7,374 lobsters were collected during 2010 and 2011. Of these lobsters, 568 were captured using standard traps and 6,543 using ventless traps. The remaining 263 lobsters were collected during SCUBA surveys. The mean size (in mm CL) of the lobsters captured in standard traps was 61.98 ± 0.61 mm, which was not significantly different from the mean size of lobsters caught in ventless traps (Fig. 1.5; 62.38 ± 0.12 mm; P-value = 0.46, unpaired *t*-test). The mean size of lobsters on the bottom (48.06 ± 0.90 mm), collected by SCUBA divers, was significantly different from the mean size of lobsters captured in either type of trap (P-value < 0.0001, unpaired *t*-test).

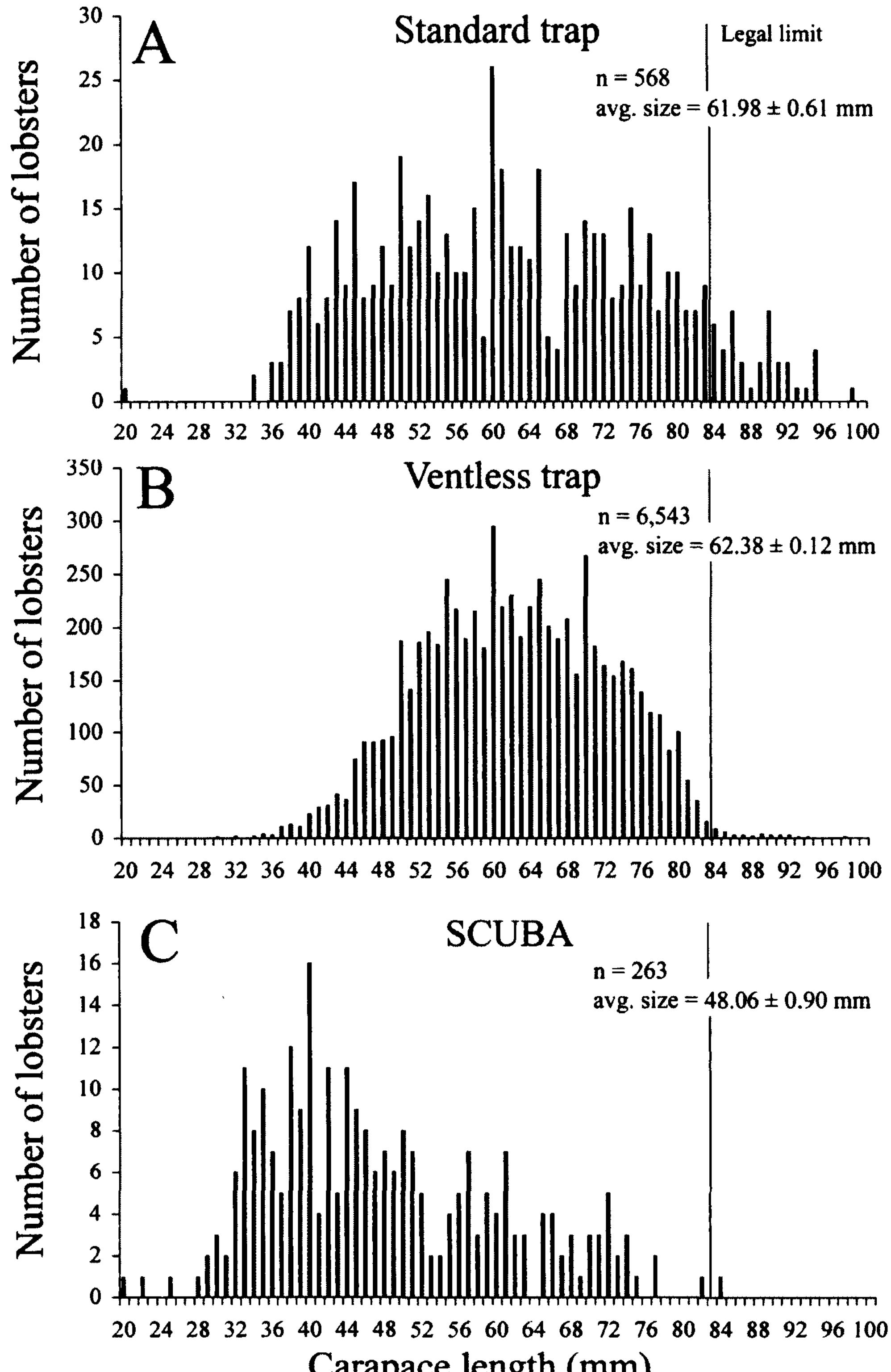

Figure 1.5. A) The size frequency distribution of lobsters captured in standard traps, B) ventless traps, and C) SCUBA surveys between June and October of 2010 and 2011. The vertical line indicated above marks the minimum legal limit for lobsters in New Hampshire. Note the Y-axis is different for each graph.

Assessing the cumulative catch curve of each sampling technique showed that all three gear types - standard traps, ventless traps, and SCUBA surveys - caught significantly different sizes of lobsters (Fig. 1.6; KS-value < 0.05, two-sample Kolmogorov-Smirnov test).

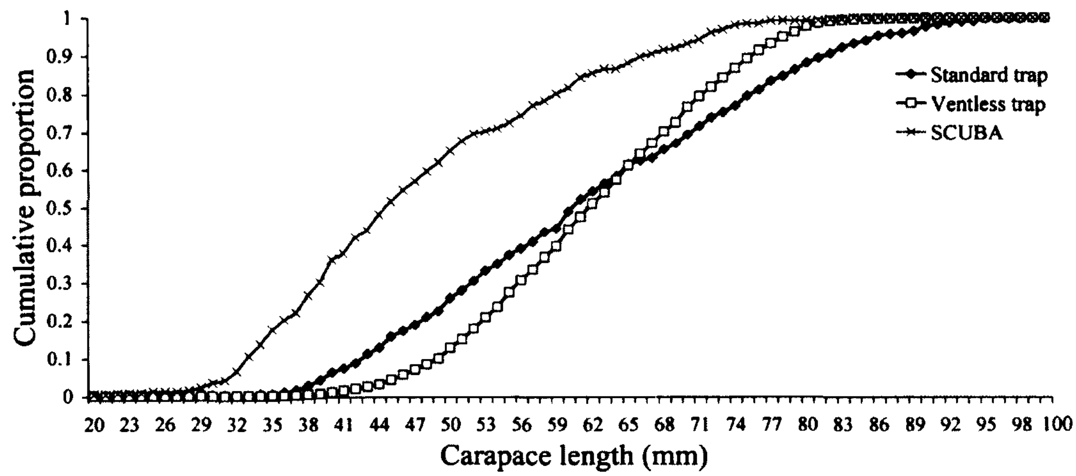

Figure 1.6. Cumulative catch curve of all lobsters (n = 7,374) collected in 2010 and 2011. Lobster size was compared based on the type of gear that was used to collect the lobster.

Catch data

While the average size of lobsters caught in standard and ventless was similar, there were significantly more lobsters caught in ventless traps compared to standard traps (Fig. 1.7A; P-value < 0.0001, unpaired *t*-test). Specifically, there were 93.78% more lobsters collected in ventless traps than in standard traps after fishing for 24 hours. When the lobster density was relatively low (i.e. June), this difference was not as pronounced as during periods of higher lobster density. For example, the average ventless trap CPUE in August was 26 ± 2.46 after 24 hours while the average standard trap CPUE was only 1.23 ± 0.46. In contrast, ventless trap CPUE in June was 16.15 ± 2.1 while standard traps captured 1.43 ± 0.22 lobsters after a 24-hour soak. A similar trend was observed after fishing traps for 48 hours (Fig. 1.7B), with ventless traps capturing significantly more lobsters than standard traps, particularly during periods of high density (P-value <0.0001, unpaired t-test). Considering all 24- and 48-hour catch, the geometric mean for ventless trap CPUE was approximately 10x the CPUE for standard traps (17.59 vs 1.63). These two soak times were chosen to represent typical differences in standard and ventless trap catch. Note that most of the soak times produced similar results.

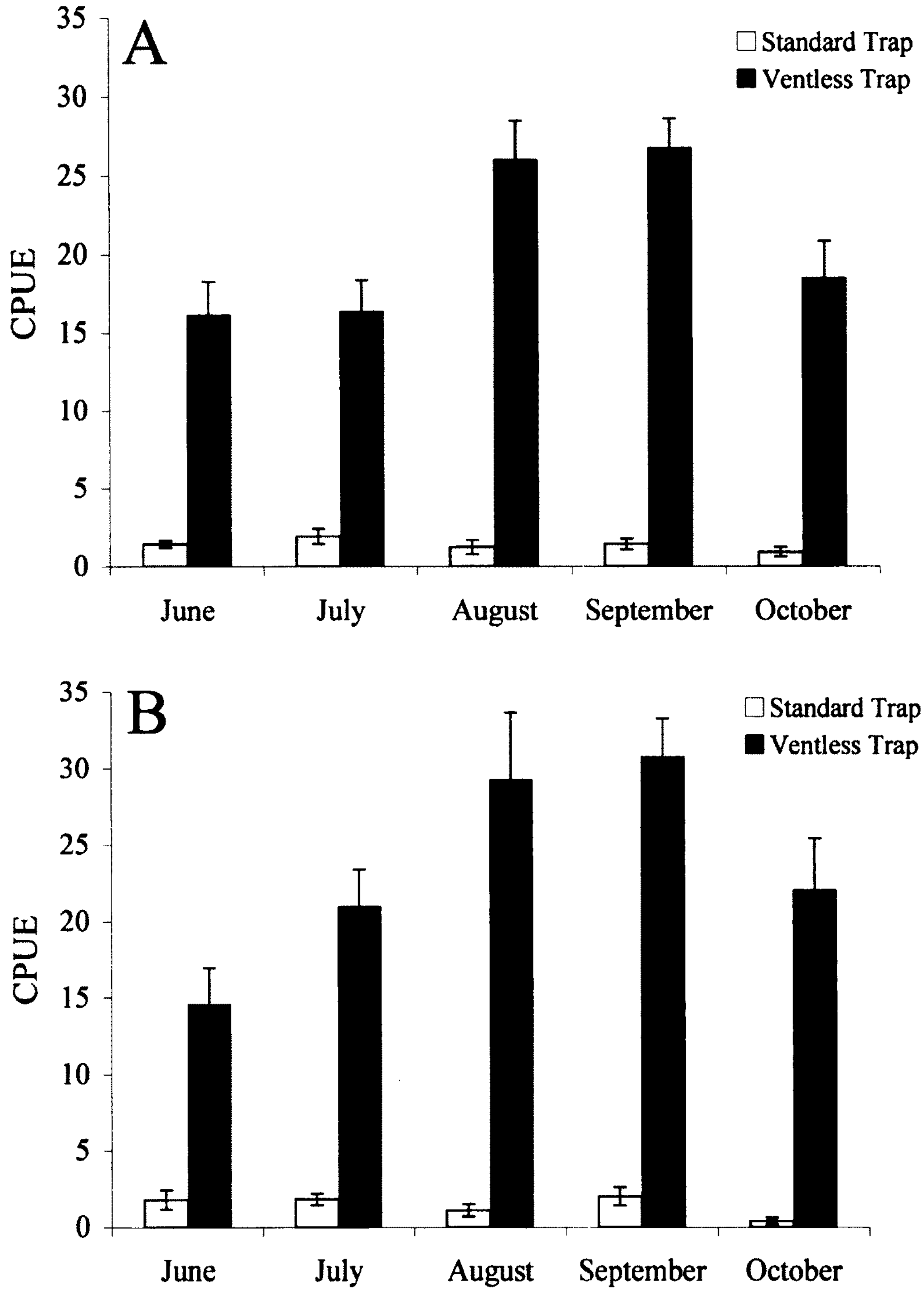

Figure 1.7. CPUE in standard traps and ventless traps after A) 24 hours and B) 48 hours, collected from June through October 2010. There was a significant difference between standard trap CPUE and ventless trap CPUE after 24 hours (A; n = 19) and after 48 hours (B; n = 18) for each month (P-value < 0.0001, unpaired *t*-test). Y error bars indicate ± SEM of all catch collected after 24 and 48 hours.

Trap saturation

Standard and ventless traps were fished for soak times ranging from 2-72 hours. In general, ventless trap CPUE increased steadily for the first 16-24 hours and then leveled off, while standard trap CPUE changed little over this same time period (Fig. 1.8). Regression analysis showed no relationship between standard trap catch and soak, yet showed a significant logarithmic increase in ventless trap catch as soak time increased ($r^2 = 0.0045$ and $r^2 = 0.9523$ for standard and ventless traps, respectively).

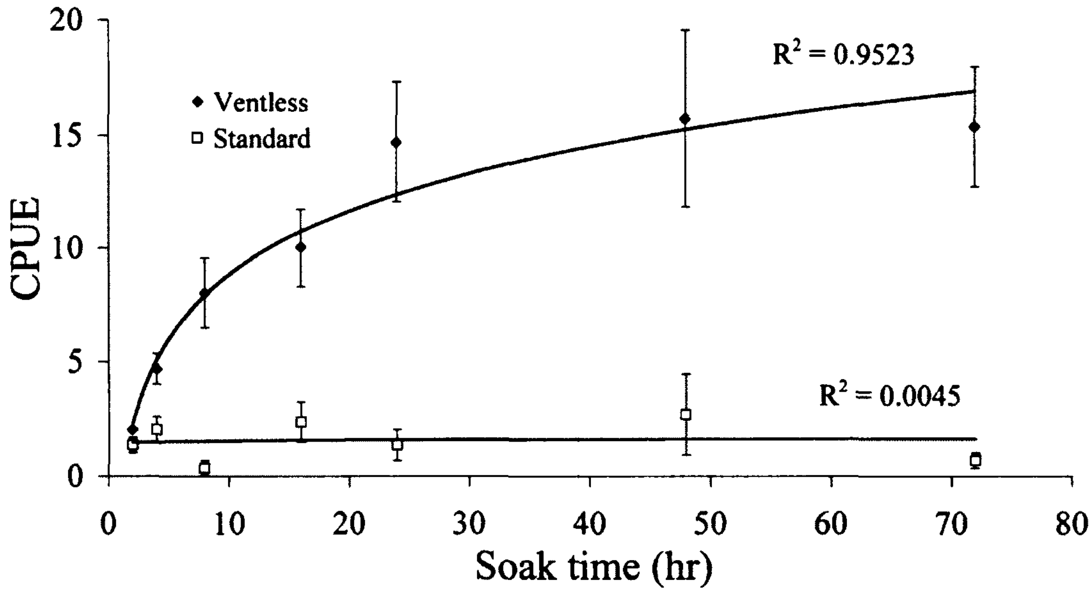

Figure 1.8. An example of data obtained from one trap saturation trial. There were three standard and ventless traps sampled at each soak time.

Ventless trap saturation at different lobsters densities

While there was no significant difference between catch at any time points for standard traps in 2010 (Fig. 1.9A; P-value = 0.7485, one-way ANOVA) and 2011 (Fig. 1.9B; P-value = 0.6847, one-way ANOVA), there were differences at certain time points for ventless traps. Specifically, ventless traps appeared to saturate 16 hours (Fig. 1.9A) and 24 hours (Fig. 1.9B) after deployment.

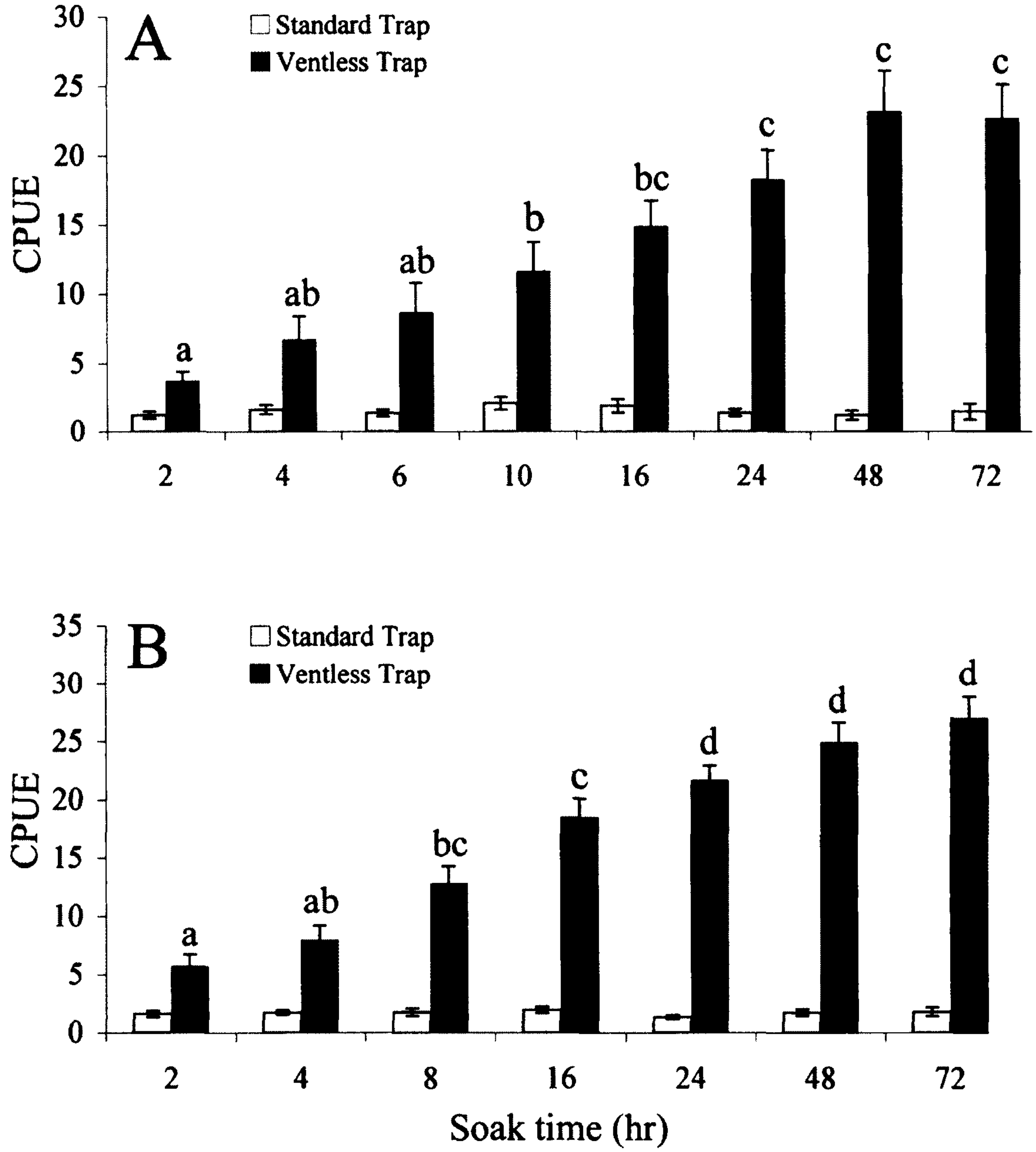

Figure 1.9. Comparison of catch in ventless and standard traps during A) 2010 and B) 2011. There was a significant difference between catch in ventless and standard traps after most individual soak times (P-value < 0.0001, one-way ANOVA) in 2010 (n = 13-23 trap pairs/soak time) and 2011 (n = 17-53 trap pairs/soak time). Differences between catch in ventless traps across soak times are indicated by letters above the bars. Note that all one-way ANOVAs were followed by Tukey Multiple Comparison Tests.

While ventless traps appear to saturate between 16 and 24 hours (Figs. 1.9A & B), catch at all time points tended to be greater at high lobster densities relative to low lobster densities (Fig. 1.10). For example, the geometric mean of CPUE after 24 hours was 14.2 and 28.5 for low and high lobster densities, respectively. Logarithmic regression analyses were performed on the average CPUE of 5 trials conducted at high lobster densities and on the average CPUE of three trials conducted low lobster densities. These two different density ranges were chosen to illustrate that ventless traps saturate at different final catch values. In both low and high densities, there were strong relationships between catch and soak time ($r^2 = 0.9401$ and $r^2 = 0.9661$ for ventless trap CPUE collected during high lobster densities and low lobster densities, respectively).

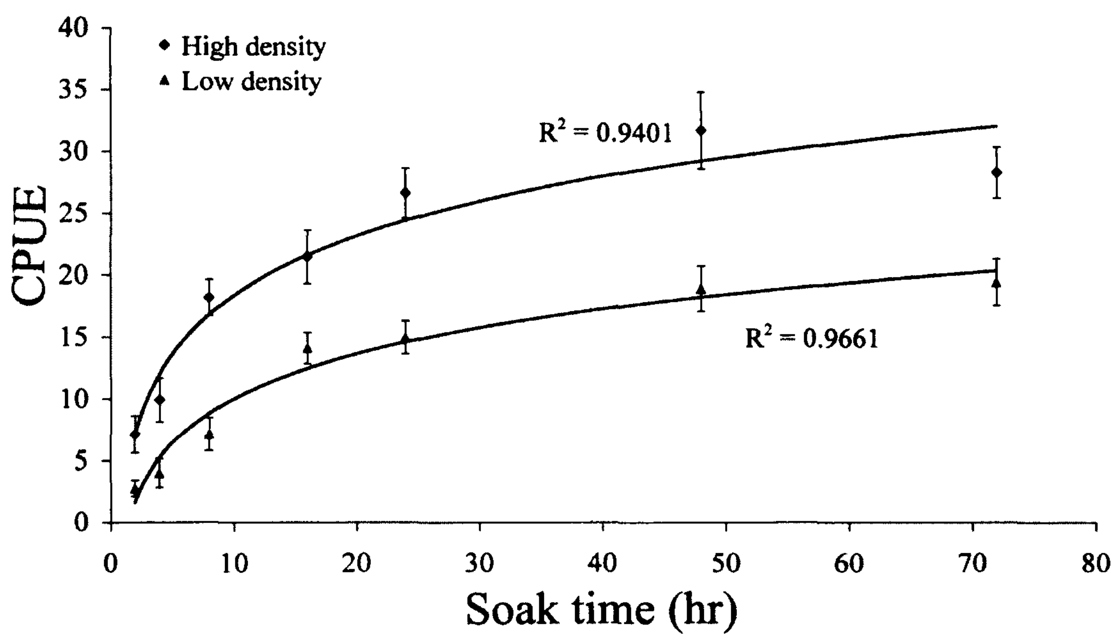

Figure 1.10. Average CPUE collected in ventless traps at two densities: low ($0 < 0.04$ lobsters/m^2; n = 5 trials) and high ($1 < 1.5$ lobsters/m^2; n = 3 trials). Trial details are provided in Table 1.1. Logarithmic regression analyses yielded coefficients of determination between 0.9401 and 0.9661.

Using segmented linear regression analyses, saturation curves were examined at low and high densities to determine at which time points traps begin to saturate. Catch rate at low densities was reduced from 0.8 lobsters/hr to 0.09 lobsters/hr after 17.11 hours and, at high densities, a reduction from 1.0 to 0.03 lobsters/hr did not occur until 20.92 hours after setting the traps (Fig. 1.11).

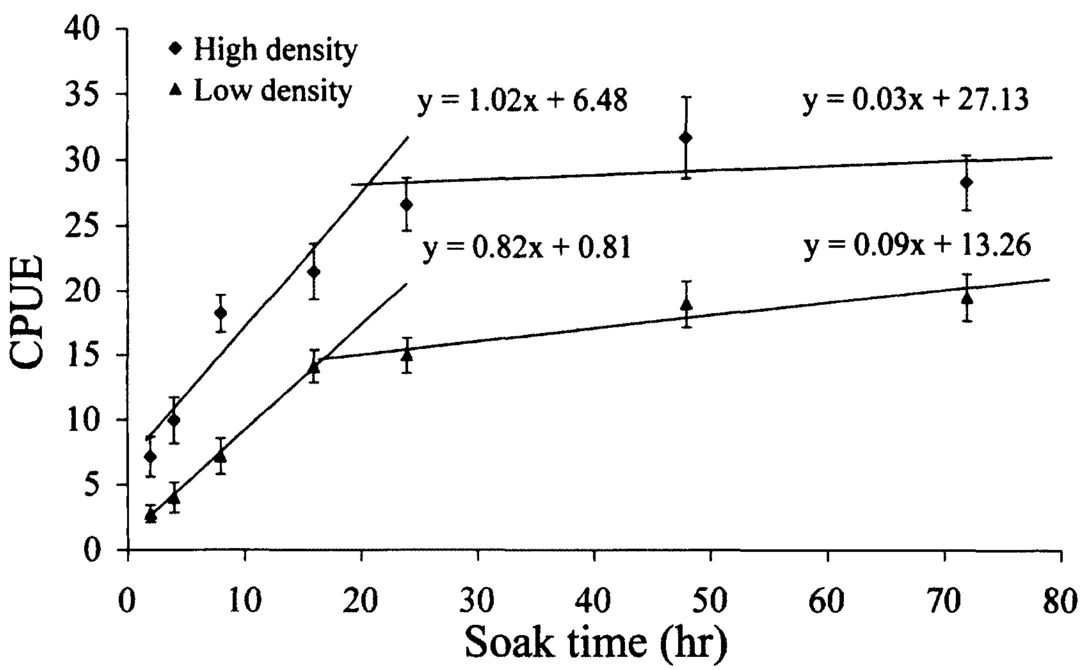

Figure 1.11. Catch rates at high and low lobster densities based on average CPUE in ventless traps. At a high density of 0.114 ± 0.028 lobsters/m^2, rate of catch was 1.02 lobsters/hour before leveling off after approximately 20.92 hours. Catch rate at the low density (0.024 ± 0.007 lobsters/m^2), unlike that of the high density, slowed down after 17.11 hours.

The relationship between ventless trap catch and lobster density was examined for each of the time intervals that were studied in both 2010 and 2011: 2, 4, 16, 24, 48, and 72 hours. The strongest overall relationship between CPUE and lobster density were obtained after soaks of 16, 24 and 48 hours (16 hr: $r^2 = 0.4075$, 24 hr: $r^2 = 0.4312$, 48 hr: $r^2 = 0.6578$, Fig. 1.12A). Linear regression analyses performed on CPUE from all aforementioned soak times are summarized in Table 1.2.

Soak time (hr)	**2010 r^2**	**2011 r^2**	**Combined 2010 and 2011 r^2**
2	0.1481	0.3623	0.1852
4	0.2503	0.2569	0.2494
16	0.9849	0.2057	0.4075
24	0.3194	0.6532	0.4312
48	0.7294	0.5469	0.6578
72	0.0931	0.4507	0.2098

Table 1.2. Coefficients of determination summarizing CPUE in ventless traps versus lobster density for different soak times. Among most time trials (2010 and 2011, Table 1.1), there was a strongest overall relationship between lobster density and catch after 16-48 hours.

Linear regression analyses were performed on standard trap CPUE collected after 16, 24 and 48 hours since ventless trap catch at these same soak times exhibited the strongest relationship with lobster density (Fig. 1.12B). In general, standard trap catch did not fit increasing lobster density as well as ventless trap catch (16 hr: $r^2 = 0.532$, 24 hr: $r^2 = 0.0753$, 48 hr: $r^2 = 0.532$).

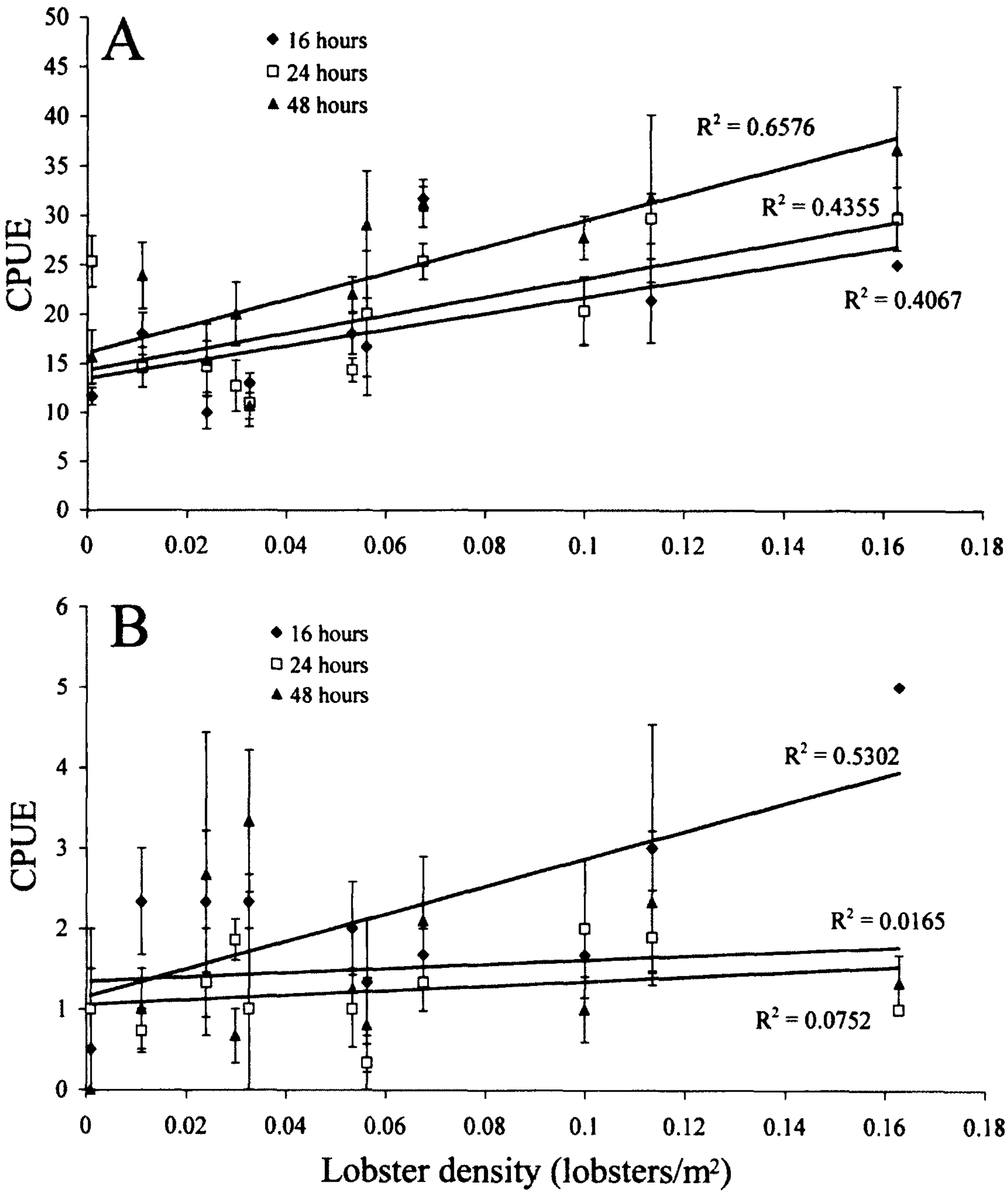

Figure 1.12. CPUE collected after soaks of 16, 24, and 48 hours for A) ventless traps and B) standard traps. Each point represents CPUE averaged from 2010 and 2011 catch data (n = 3-7 traps/soak time).

Size frequency composition of catch across immersion periods

The average size of the lobsters captured after each soak time was evaluated to determine if the mean size of lobsters changed with increasing soak times (Fig. 1.13). For each soak time, the size of lobsters collected during all 12 trials were averaged and compared to sizes at different soaks. There was no strong relationship between the size of lobsters and increasing soak time ($r^2 = 0.096$; P-value = 0.065, one-way ANOVA).

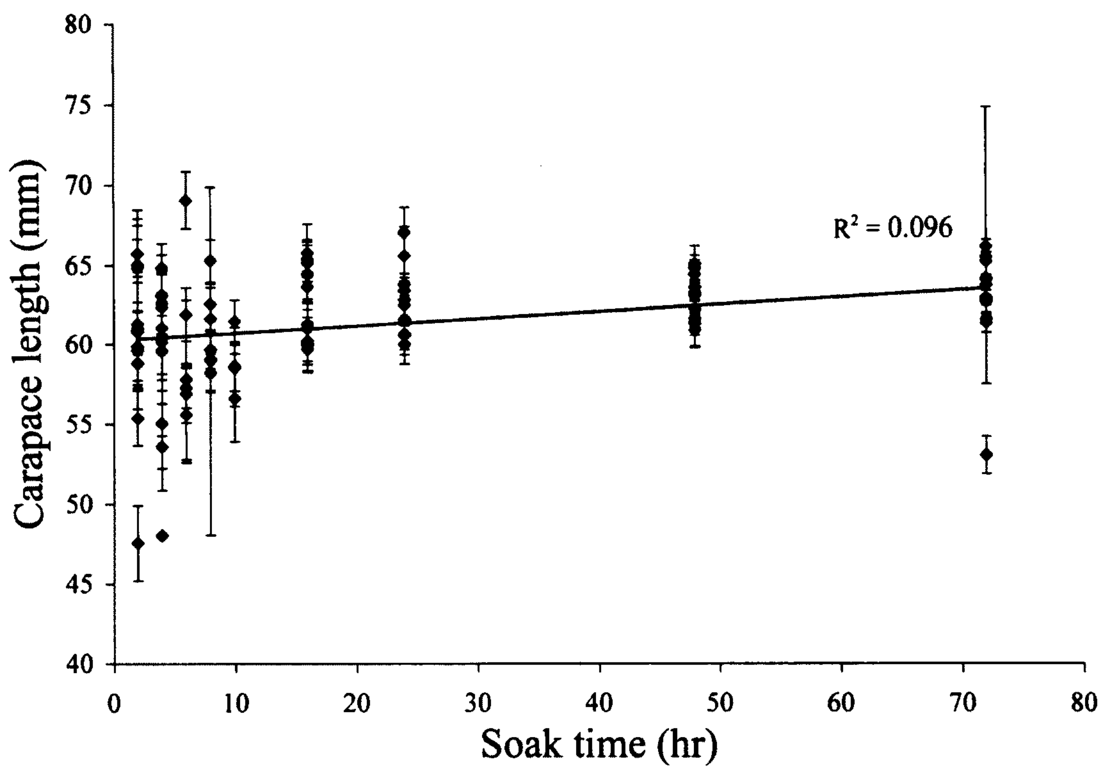

Figure 1.13. Mean sizes (± SEM) of lobsters collected in ventless traps (n = 3-7 traps/point) at each time interval. Sizes of all catch collected throughout the 12 trials (5 from 2010 and 7 from 2011) are presented here.

In order to determine if the size of lobsters captured changed over time, lobsters were first categorized into three size classes, as done by Watson and Jury (in press): < 65 mm, 65-83 mm, and > 83 mm. Then the CPUE, based on these parameters, were determined at each soak time. In general, while the catch of smaller lobsters was always higher than larger ones, there was no clear trend over time for any of the size classes examined, either at low or high lobster densities (Fig. 1.14).

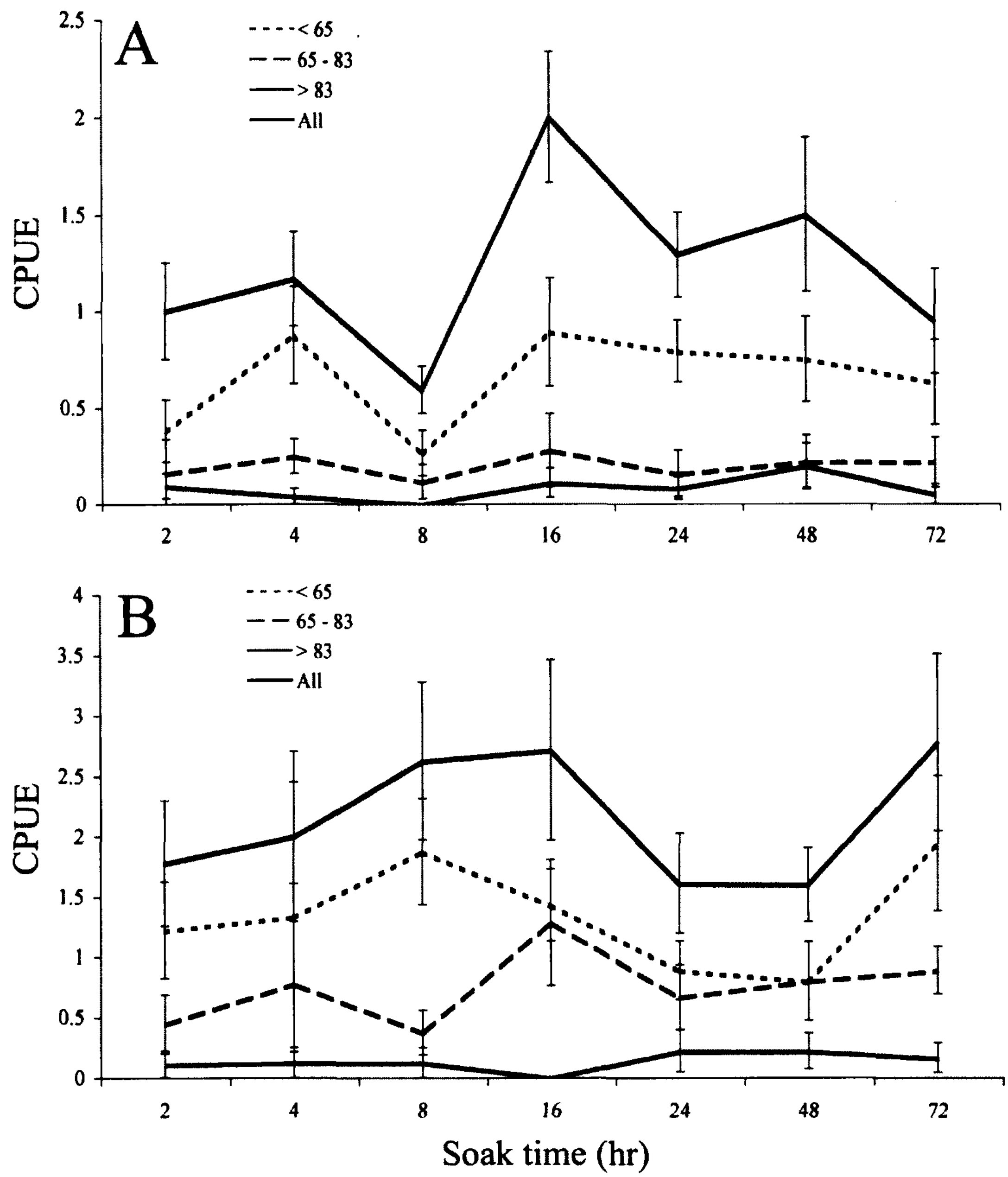

Figure 1.14. CPUE of different size classes of lobsters in ventless traps at low lobster densities (A; n = 5 trials) and high lobster densities (B; n = 3 trials).

Sex ratio of catch in different gear types

Each type of trap captured more male lobsters than female lobsters (Fig. 1.15). This was not necessarily a function of catchability because SCUBA divers also captured more male lobsters than female lobsters. This trend was evident in both 2010 and 2011.

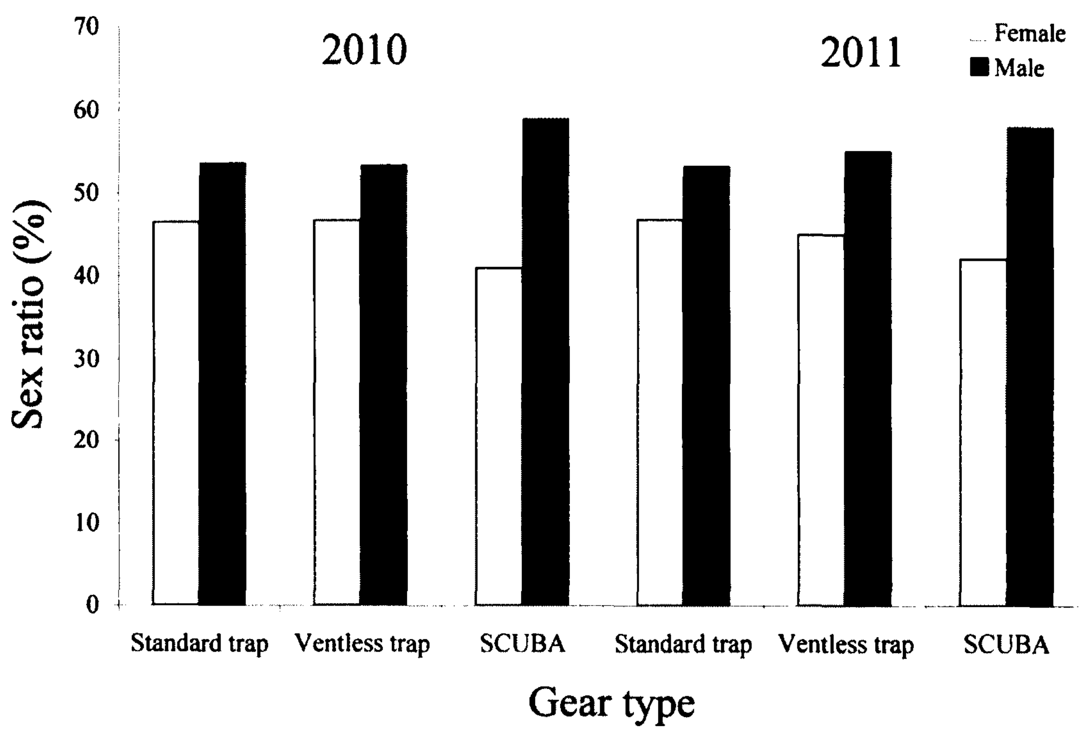

Figure 1.15. Sex ratio of lobsters caught in different gear types during 2010 and 2011. In both years, male lobsters were more prevalent in catch.

Bait degradation

Bait loss was compared between standard and ventless traps each at different soak times (Fig. 1.16), ranging from 2-96 hours. Significantly more bait was lost in standard traps than in ventless traps (P-value < 0.0001, unpaired *t*-test). Specifically, more bait was consumed during three soak times (24, 48 and 72 hours).

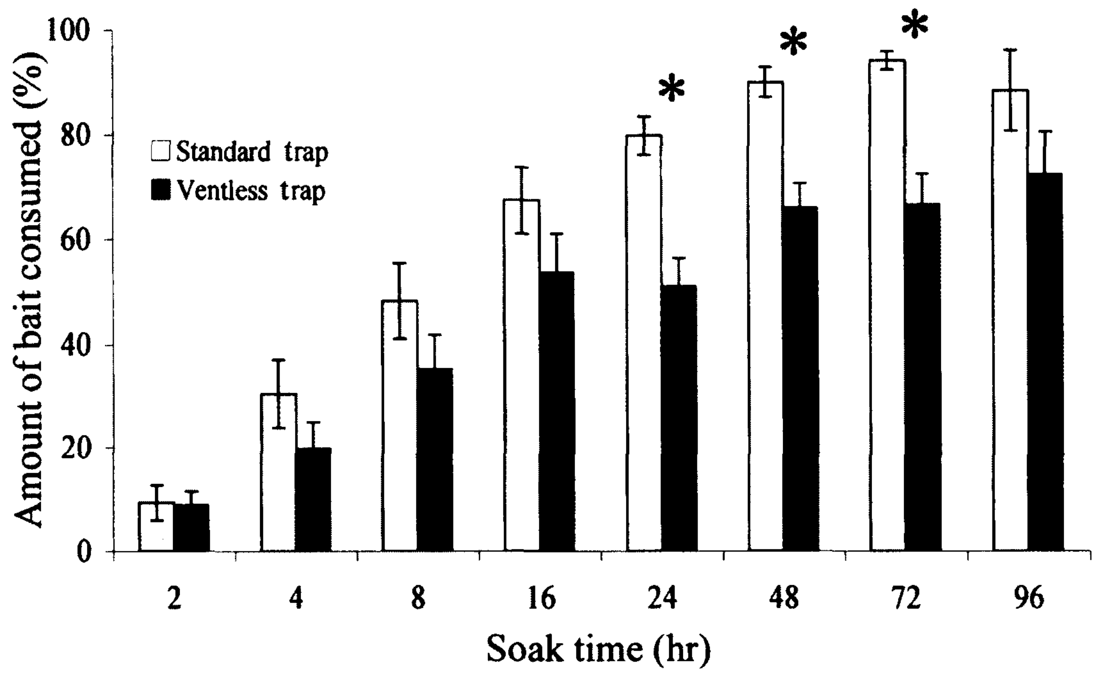

Figure 1.16. Bait consumption in ventless and standard traps per soak time. There was significantly more bait loss in standard traps during the following soak times: 24, 48, and 72 hours (P-value < 0.0001, one-way ANOVA).

Discussion

While it is now widely established that standard lobster traps provide an inaccurate index of both the size structure and density of lobsters in a given area, the goal of this study was to determine the relationship between these variables and the catch obtained in ventless traps. As expected, we found that ventless traps typically captured 3-5 times more lobsters than standard traps, but the mean size of the lobsters captured in ventless traps was not significantly different than those retained by standard traps. Finally, while standard traps saturated very early in a soak period, ventless traps consistently saturated between 16 and 24 hours, at all densities tested.

Lobster movement and density

American lobsters undergo seasonal movements between inshore and offshore waters (Cooper & Uzmann, 1971; Estrella & Morrissey, 1997; Watson *et al.*, 1999). Cues that cause lobsters to migrate include changes in salinity (in estuaries; Jury *et al.*, 1994a,b; 1995; Watson *et al.*, 1999), increases and decreases in water temperatures (Cooper & Uzmann, 1971; Pezzack & Dugan, 1986; Karnofsky *et al.*, 1989; Jury *et al.*, 1995; Estrella & Morrissey, 1997; Watson *et al.*, 1999), and wave surge/storms (Goldstein & Watson, 2012). Along the coast of NH, probably the strongest predictor of lobster movements is water temperature. The thermosensitivity of American lobsters allow them to detect and, thus, avoid extreme temperatures (Crossin *et al.*, 1998; Jury & Watson, 2000) and move to areas that are at their preferred temperature of approximately 16°C (Crossin *et al.*, 1998). As a result, lobsters tend to move inshore in the spring/summer because water temperatures tend to be higher along the coast. In the late fall, lobsters then move offshore as inshore temperatures are dropping. This, in part, gives rise to the large seasonal fluctuations in lobster density throughout inshore NH waters.

In this study, lobster movements to coastal waters in the spring were correlated with increasing water temperatures and, likewise, decreases in lobster densities were associated with decreasing inshore temperatures in the fall (Fig. 1.4). The density of lobsters and water temperatures off the coast of Wallis Sands State Beach began to increase in June of each year. Both peaked between August and September before decreasing in fall. A similar trend has been observed in two previous studies at this same study site (Jury *et al.*, 2001; Watson & Jury, in press).

The relationship between lobster catch and water temperature is a longstanding observation, and there have been many explanations put forth to explain this phenomenon. The two most commonly accepted views are: 1) as water temperatures increase, lobsters become more active and enter traps more frequently leading to increased catch and, 2) lobsters move into areas that are at their preferred water temperature thus increasing lobster density and catch (Drinkwater *et al.*, 2006). The use of SCUBA surveys in this study clearly demonstrated that lobster density was very closely correlated with water temperatures and, therefore, the latter hypothesis for the relationship between catch and water temperature is strongly supported by this study.

Since inshore and offshore waters experience such large lobster density fluctuations, managing the lobster fishery can be especially challenging. The use of diver surveys is both costly and limited in spatial coverage. Standard traps are very useful, but the correlation between catch in standard traps and lobster density is likely to be poor, based on observations of lobster traps (Jury *et al.*, 2001; Watson and Jury, in press). Therefore, fishery-independent sampling methods, such as ventless trap surveys, have been implemented on a regular basis by Canada and several state agencies in New England (DMR, 2011). Because such techniques are widely used, it is critical that they be calibrated so that biologists and managers understand how accurate the data are that are obtained from these ventless trap surveys. Obtaining those calibration data was a major focus of this study.

Ventless and standard traps

At the study site used for this investigation, there were very few legal-sized lobsters and the mean size of the lobsters observed during SCUBA surveys was 48.06 ± 0.90 mm CL. Therefore, most of the lobsters collected during this study were sublegal-sized (>90%). Ventless and standard traps had similar size selectivity, capturing lobsters that had CL of 62.38 ± 0.12 mm and 61.98 ± 0.61 mm, respectively. Although the mean size of lobsters captured by SCUBA divers was significantly smaller than the average size of lobsters captured in either type of trap, this was not due to the fact that the traps failed to retain lobsters on the small end of the size frequency range (Fig. 1.5). Rather, traps tended to capture many more lobsters in the 60 to 80 mm CL size range than were observed on the bottom.

As expected, based on previous studies (Glenn *et al.*, 2007; Courchene & Stokesbury, 2011) ventless traps caught significantly more lobsters than standards traps (P-value < 0.0001, unpaired *t*-test). This finding stood true for all months and all lobster densities. Based on observations of ventless traps using video cameras, the major difference between the traps was that very few lobsters escaped from ventless traps because they tended to accumulate in the parlor. These video data will be presented in Chapter Two.

Sex ratios of all catch data were calculated to better characterize the lobster populations. Both types of traps caught more male lobsters than females. In fact, between 72 and 87% of the lobsters captured between 2010 and 2011 were male. These data are consistent with previous findings for ventless traps, demonstrating that male lobsters tend to represent a large proportion of catch (Tremblay *et al.*, 2006; Courchene & Stokesbury, 2011). This skewed sex ratio in the catch could be due to differential catchability of male vs. female lobsters, or it could represent the actual sex ratio in this area. Because SCUBA surveys yielded results that were also skewed towards males, it appears as if traps are accurately representing the population on the bottom. It is possible that there are more males in this area because they tend to aggregate in warmer, shallower waters in comparison to females (Watson *et al.*, 1999).

The Relationship between Catch and Lobster Density

One of the major goals of this study was to determine which type of trap provided the best index of the density of lobsters on the bottom (estimated using SCUBA surveys).

Our long-term goal is to determine if catch in either type of trap can be used effectively to estimate lobster density. Therefore, one part of our analysis was to determine if there was a correlation between catch and lobster density. Because lobster density varied with the season, and thus water temperature, it has not escaped our attention that water temperature is a co-variable in this study that we could not control.

In 2010, lobster density increased from 0.03 ± 0.005 lobsters/m^2 in June to 0.16 ± 0.004 lobsters/m^2 in September, while in 2011 it fluctuated between 0.04 ± 0.008 lobsters/m^2 and 0.05 ± 0.008 lobsters/m^2 in this same time period (Fig. 1.4). In both years as lobster density increased, so did catch. For example, in 2010 the 48-hour CPUE increased from 10.67 ± 2.19 to 36.67 ± 6.33 and from 15.33 ± 3.67 to 31.67 ± 8.45 in 2011, which were in accordance with increasing lobster density (Fig. 1.12A). A similarly strong relationship was observed among ventless traps after having fished for 16 and 24 hours (Fig. 1.12A). Ventless trap catch collected after other soak times (2, 4, and 72 hours) also exhibited fairly strong relationships with increasing lobster density, illustrating that ventless traps correlate with relative lobster abundance better than standard traps (Table 1.2). Overall, standard trap catch had a weaker relationship with increasing lobster density (Fig. 1.12B). This exemplified that standard traps are poor indicators of lobster abundance, as supported by Watson and Jury (in press).

Trap saturation

While gear saturation occurs in many fisheries assessments, its effects are not well understood (Miller, 1979). In this study, ventless and standard trap pairs were fished for soak periods ranging from 2 to 96 hours. After each trial (Table 1.1), cumulative CPUEs in both trap types were analyzed over time (Fig. 1.8). The saturation curves presented in this study demonstrated how catch in ventless traps tended to increase rapidly during the first

16 to 24 hours of a soak before beginning to plateau (Figs. 1.8 & 1.9). Previous studies have examined the relationship between soak time and catch in Antillean fish traps, Golden king crab pots, and standard lobster traps. These studies yielded similar curves, illustrating that the asymptotic property of catch is a function of soak time (Munro, 1974; Auster, 1985; 1986; van Tamelen, 2001). In contrast, standard trap CPUE was not significantly different across all soak periods (Fig. 1.8; P-value = 0.4465; one-way ANOVA) and tended to plateau starting 4 hours after deployment (Fig. 1.9A; P-value = 0.4948, unpaired *t*-test) and in 2011 (Fig. 1.9B; P-value = 0.1593, unpaired *t*-test). This is consistent with data from two previous studies that focused on standard traps in the same area (Jury *et al.*, 2001; Watson and Jury, in press). Because catch in standard traps is independent of soak time and only loosely correlated with density (Fig. 1.12B), we focused most of our attention on ventless trap data. It should be noted, however, that our data includes all lobsters, not just legal lobsters. Two different studies (Jury *et al.*, 2001; Watson & Jury, in press) have demonstrated that larger lobsters tend to enter traps later in a soak, and thus for a commercial lobstermen it certainly makes sense to continue to fish traps for long soak times in order to optimize catch of larger lobsters.

Overall, it appears as if ventless traps tend to saturate between approximately 16 and 24 hours. In 2010, there was no statistical difference between the CPUE in ventless traps pulled at the following time intervals: 16, 24, 48, and 72 hours (Fig. 1.9A; P-value = 0.4611, Tukey's Test) and, in 2011, the same was true for soak times of 24, 48, and 72 hours (Fig. 1.9B; P-value = 0.0804; Tukey's Test). Therefore, after 16 hours in 2010 and 24 hours in 2011, CPUE remained relatively constant. There is thus no apparent advantage to collecting data from ventless traps for more than 24 hours, except perhaps if the goal is to capture some larger lobsters (Jury *et al.*, 2001; Watson & Jury, in press).

The three main factors that have been proposed to give rise to trap saturation are: 1) traps fill with lobsters, or fish in the case of Prchalová *et al.* (2011), to the point where they cannot hold anymore; 2) once some lobsters get into a trap, especially larger lobsters, they prevent other lobsters from entering (Richards *et al.*, 1983; Jury *et al.*, 2001; Watson & Jury, in press) and; 3) as bait deteriorates it stops attracting lobsters (Karnofsky & Price, 1989). The data obtained in this study does not support any of these three hypotheses. First, at all densities tested, ventless traps saturated, but at different final catch values. This indicates that saturation was not a function of the number of lobsters in the trap because if that were the case, then all of the traps would have saturated at the same CPUE value. This is not to say that in areas with a high density of lobsters, especially large ones, ventless traps will not reach a point where CPUE levels off because they simply cannot hold more animals. For example, in some locations in Massachusetts, ventless traps have been reported to catch at least 80 lobsters (Tracy Pugh, personal communication), well above the maximum average of 30 lobsters captured in this study site (Fig. 1.10).

We can also discount the hypothesis about bait attraction for two reasons. First, standard traps saturated after four hours, long before the bait either deteriorated or was all eaten. Second, there was actually more bait left in ventless traps after 2-3 days than in standard traps (Fig. 1.16). Because most of the animals in ventless traps congregated and became trapped in the parlor, there was little bait consumed and approximately 50% of it remained after 24 hours compared to the 20% left in standard traps. Since more bait was lost in standard traps relative to ventless traps, this suggests that lobsters continually enter and exit standard traps, which would account for the reduced bait. In contrast, because ventless traps accumulate lobsters in the parlor, the same lobsters cannot repeatedly exit and enter and consume the bait. Importantly, this also suggests that ventless traps are reducing the number of lobsters in the vicinity of the trap, while standard traps do not. Our working hypothesis is that this reduction in the number of catchable lobsters in the vicinity of ventless traps is one of the primary causes of traps saturation (Chapter Two). It is important to acknowledge the fact that ventless and standard traps were fished in pairs, 10 meters apart from one another. The area of bait attraction is approximately 11 meters from the trap, which may suggest that catch in one trap could reduce catch in an adjacent trap (Watson *et al.*, 2009). Pickering *et al.* (2010), however, tested this theory and found that there was no significant difference between connected traps.

Finally, several studies with lobsters and other crustaceans have provided observations and data suggesting that animals in a trap, through antagonistic interactions, reduce the rate of entry of new animals (Richards *et al.*, 1983; Addison, 1995; Addison & Bannister, 1998; Jury *et al.*, 2001; Barber & Cobb, 2009). While these types of interactions also occurred in this study, it was not evident that they limited catch. This argument is similar to the one used to reject the "biomass" hypothesis. If interactions limited catch, then you might expect these interactions to be very intense at high densities and thus you would expect that there would be a CPUE that was maximal. However, as explained above, this does not occur. The maximum CPUE tends to go up as density increases.

Another hypothesis that we sought to test in this study was that traps saturate faster at higher densities. When we developed this hypothesis, we assumed, wrongly, that traps would saturate at about the same maximum catch, at all densities, but this would happen faster at higher densities, for the reasons cited above. Preliminary analyses of catch collected at two densities, 0.024 ± 0.007 lobsters/m^2 and 0.114 ± 0.028 lobsters/m^2, demonstrated that ventless traps saturate at approximately the same time at different densities, but the catch at saturation (maximal catch) increases with higher densities. To investigate this further, catch data were grouped according to the density at which they were collected so as to provide sufficient data for statistical analyses (Fig. 1.10). These density ranges were: $0 < 0.4$ lobsters/m^2 and $1 < 1.5$ lobsters/m^2. Catch collected during the two density groups began to saturate within 16 to 24 hours, similar to previous findings (Figs. 1.8 & 1.9). Thus, in general, the onset of trap saturation occurs after 16 hours at most densities, indicating that the time to reach trap saturation is not a useful index of lobster density on the bottom.

Maximum catch in ventless traps correlated with lobster density. CPUE ranged from 19.39 ± 1.87 at the low densities to 31.6 ± 3.1 high densities (Figs. 1.10 & 1.11). At low densities, lobsters entered ventless traps at a rate of approximately 0.82 lobsters/hour between the 2- and 16-hour soaks, after which the catch rate decreased to 0.09 lobsters/hour. The entry rate for lobsters the higher densities was 1.02 lobsters/hour from 2 to 16 hours, before leveling off at 0.03 lobsters/hour. Therefore, both rate of catch, in lobsters/hour, or maximal catch after 24 hours, could provide useful indices of lobster abundance.

Ventless trap surveys are intended to estimate lobster abundance and size structure. To calibrate this sampling method, the present study examined the relationship between lobster density and ventless trap CPUE after each of the following soak times: 2, 4, 16, 24, 48, 72, and 96 hours. After performing linear regression analyses on 2010 and 2011 catch data, 16-, 24-, and 48-hour CPUE exhibited the strongest overall relationship with lobster density (Fig. 1.12). However, these data could be strengthened if we were to focus only on the size classes of lobsters that are most readily retained in traps. Because we did not obtain sizes for all the lobsters when we conducted dive surveys, as we did not want to disturb them by picking them up, we do not have sufficient data to compare, for a given trial, the catch of lobsters of a given size with the density of lobsters of the same size.

This study has demonstrated that ventless traps have the potential to provide a much more accurate snapshot of the lobster population on the bottom in any given location. Importantly, it demonstrates that catch in ventless traps correlates fairly well with lobster densities and that if this approach is going to be used in the future, our data provide some guidance about which soak times might provide the most accurate indices of abundance. These data show that trap saturation is a very interesting and important factor when assessing catch in both ventless and standard traps. The following chapter will discuss this and other possible causes of trap saturation, particularly among ventless traps.

CHAPTER 2

UNDERWATER VIDEO SURVEILLANCE, A MEANS TO UNDERSTANDING LOBSTER TRAP SATURATION

Abstract

Gear saturation is complex and not well understood. It can potentially bias stock assessment data derived from trap-based fisheries. Some American lobster (*Homarus americanus*) abundance estimates are based on catch data and are, therefore, subject to the saturation effect. While trap saturation has been investigated in standard traps, little is known about this process in ventless traps that are currently being used for stock assessment purposes in some areas. The overall goal of the present study was to determine some of the factors that cause trap saturation in ventless traps. In Chapter One of my thesis, I demonstrated that ventless traps saturate within 16-24 hours regardless of the lobster density. In this study, I used a video surveillance system to record the behavior of lobsters in, and around, traps with the goal of using the videos obtained to understand mechanisms that might lead to trap saturation. The data obtained in the study suggest that, in contrast to standard traps that capture very few lobsters, ventless traps catch and retain most lobsters within the trapping area so that over time there are fewer lobsters left to capture. As a result, rate of entries drop after 15-18 hours and eventually entries equal escapes and catch reaches a plateau. Therefore, while saturation in standard traps appears to be due to a combination of factors, such as bait consumption and antagonistic interactions between lobsters, data from this study suggest that ventless traps saturate because they accumulate most of the catchable lobsters in the trapping area. Therefore, if we understand the fishable area of the

trap it should be possible to calculate lobster density on the bottom based on the catch of lobsters in ventless traps.

Introduction

In order to avoid overfishing the oceans, it is critical to effectively measure and monitor fish and shellfish populations. Establishing accurate abundance indices helps fisheries managers to optimize stock assessment. Catch-per-unit-effort (CPUE) is currently accepted as one of the best indicators of abundance, particularly for the American lobster, *Homarus americanus* (H. Milne-Edwards, 1837), which supports the most valuable fishery in New England.

Canada and the United States have initiated a series of programs to discourage exploitation of the American lobster fishery. The Atlantic State Marine Fisheries Commission (ASMFC) enforces various regulations that, for example, limit the total number of allowable traps and size of marketable lobsters (ASMFC, 2012b). Historically, federal and state agencies have used relative abundance indices based on fishery-dependent sampling methods such as port sampling to inform management decisions. While these data are still utilized, other methods have been introduced to supplement them. In particular, in the mid-2000s, Maine DMR and Massachusetts Division of Marine Fisheries (MADMF) initiated ventless trap surveys to better estimate relative lobster abundances (DMR, 2011; MADMF, 2009).

Determining indicators and reference points for lobster abundance, particularly those of prerecruits, is an ongoing challenge (Caddy, 2003; Steneck, 2006). However, ventless trap surveys may serve as a way to address these concerns (DMR, 2011; Watson & Jury, in press). Ventless traps, in contrast to standard commercial traps, are designed to reduce escapement of sublegal-sized lobsters (Estrella & Glenn, 2006). According to Jury *et al.* (2001), 94% of lobsters entering standard traps ultimately escape. Of the 94%

lobsters, 28% exited using the escape vent while the remaining 72% escaped through the kitchen entrance. Most of the lobsters that enter traps are not legal, so it is to the advantage of commercial fishermen to have traps that allow this degree of escapement. However, if managers desire to obtain a more accurate vision of the size frequency distribution and density of lobsters on the bottom ventless traps might have some advantages.

In Chapter One of my thesis, I presented catch data obtained from fishing ventless and standard traps for soak times ranging from 2-72 hours. While standard traps saturated within four hours, ventless traps did not saturate until 16 to 24 hours. Surprisingly, while the time to saturate was similar at different lobster densities, the final maximum catch, or the total catch at the time of saturation, was correlated with lobster density. At a low lobster density, for example, traps were "saturating" at a CPUE that was much less than the CPUE at higher densities. This suggests that ventless traps are not saturating because they are at their "capacity". In addition, I found that standard traps saturated long before the bait was used up and ventless traps still had about 40-50% of the bait left in the bait bag when they saturated. Thus, bait disappearance does not appear to be the primary mechanism underlying saturation of ventless or standard traps. Previous studies have suggested that antagonistic interactions between lobsters might play a major role in limiting the catch in standard traps (Richards *et al.*, 1983; Addison, 1995; Addison & Bannister, 1998; Jury *et al.*, 2001; Barber & Cobb, 2009). Therefore, the major goal of the study summarized in this Chapter was to use underwater video techniques to study the behavior of lobsters in, and around, ventless traps in an attempt to determine if the interactions between lobsters might also give rise to trap saturation in ventless traps.

Video surveillance allows for animals to be studied in their natural habitat without the interference of humans. For example Jury *et al.* (2001) attached a video recorder and camera to a standard lobster trap and used the system to record behaviors of lobsters in, and around, the trap. Following this study, others used similar methods to study Caribbean spiny lobster behavior near traps (Weiss *et al.*, 2006), as well as Japanese rock crab (Archdale *et al.*, 2003) and Dungeness crab behavior in, and around, crab pots (Barber & Cobb, 2009). However, despite these advances, the mechanisms underlying trap saturation are not fully understood. Several studies have concluded that trap saturation is due, in part, to the interactions between animals (Miller, 1990; Richards *et al.*, 1983; Addison, 1995; Barber & Cobb, 2009; Ovegard *et al.*, 2011). For example, Dungeness crab pots were believed to saturate as a function of increased agonistic interactions between half-entering crabs and approaching crabs (Barber & Cobb, 2009). Similar territoriality has been observed in and around lobster traps (Richards *et al.*, 1983, Addison, 1995; Jury *et al.*, 2001, Clark personal observation). Pre-stocking studies showed that standard traps containing lobsters actually reduced entry rate and, thus, catch (Richards *et al.*, 1983; Addison, 1995). These findings, combined with those of Jury *et al.* (2001), suggest that trap saturation is a function of increased agonistic interactions between lobsters in and around standard traps, which reduces the rate of entry into traps as the fill up.

The objective of this study was to enhance our current understanding of standard and ventless lobster trap saturation. The majority of data were collected from ventless traps because similar data are already available for standard traps. American lobster behavior was observed using a modification of the lobster-trap video (LTV) system used in previous studies at this same study site (Jury *et al.*, 2001; Watson & Jury, in press). This time-lapse video system made it possible to observe lobster behaviors in and around the traps. Recordings were only obtained during Day One and Day Two and the following parameters were measured while observing the recordings: 1) number of lobsters entering, escaping, and surrounding the trap each hour; 2) accumulated catch over soak time; and 3) number of half-entries, entries, and escapes. Comparing these data in both trap types at low and high densities provides insight into what causes standard traps to saturate within 4 hours and ventless traps between 16 and 24 hours (Chapter One). Based on our observations, the data presented in Chapter One, and the calculations found in the Discussion, our current working hypothesis is that ventless traps saturate after they have captured and retained the majority of the catchable lobsters in the fishable area of the trap.

Materials and Methods

Study site

All lobster-trap video (LTV) data were collected during 2010 and 2011 at a study site just offshore from the Wallis Sands State Beach in Rye, NH. A total of 14 trials (7 in 2010 and 7 in 2011) were completed throughout the study, and during each trial we obtained between one and two days worth of digital video data. Of the 14 trials, three were of standard traps and the remaining 11 were of ventless traps. A total of 20 dive surveys were performed a week before and/or after each trial to estimate lobster densities and the size composition of the lobster population. SCUBA survey methods are described in Chapter 1 (Materials and Methods).

LTV system

The LTV design was modified from the original system developed by Jury *et al.* (2001). A CCD wide view fisheye bullet camera (0.5 lux low light, 2.2-mm wide view lens, Model PC221-HR, Sony products, Tokyo, Japan) was sealed inside an underwater flashlight case and mounted on top of a PVC frame (Figs. 2.1A), 121.9 cm above the trap. The camera was connected, via an underwater cable, to a waterproof case containing a mini DVR (640 x 480 lines resolution, Model UV-K206, Unique Vision Technology Co., Ltd., Shenzhen, China) and several 12V batteries (Fig. 2.1B). The DVR was programmed to turn on at dawn and off at dusk, allowing the collection of videos for between 48 and 72 hours. Digital recordings were stored on a SDHC (16 GB) memory card and transferred to a computer for analyses after each trial. The duration of data collection were primarily limited by the batteries.

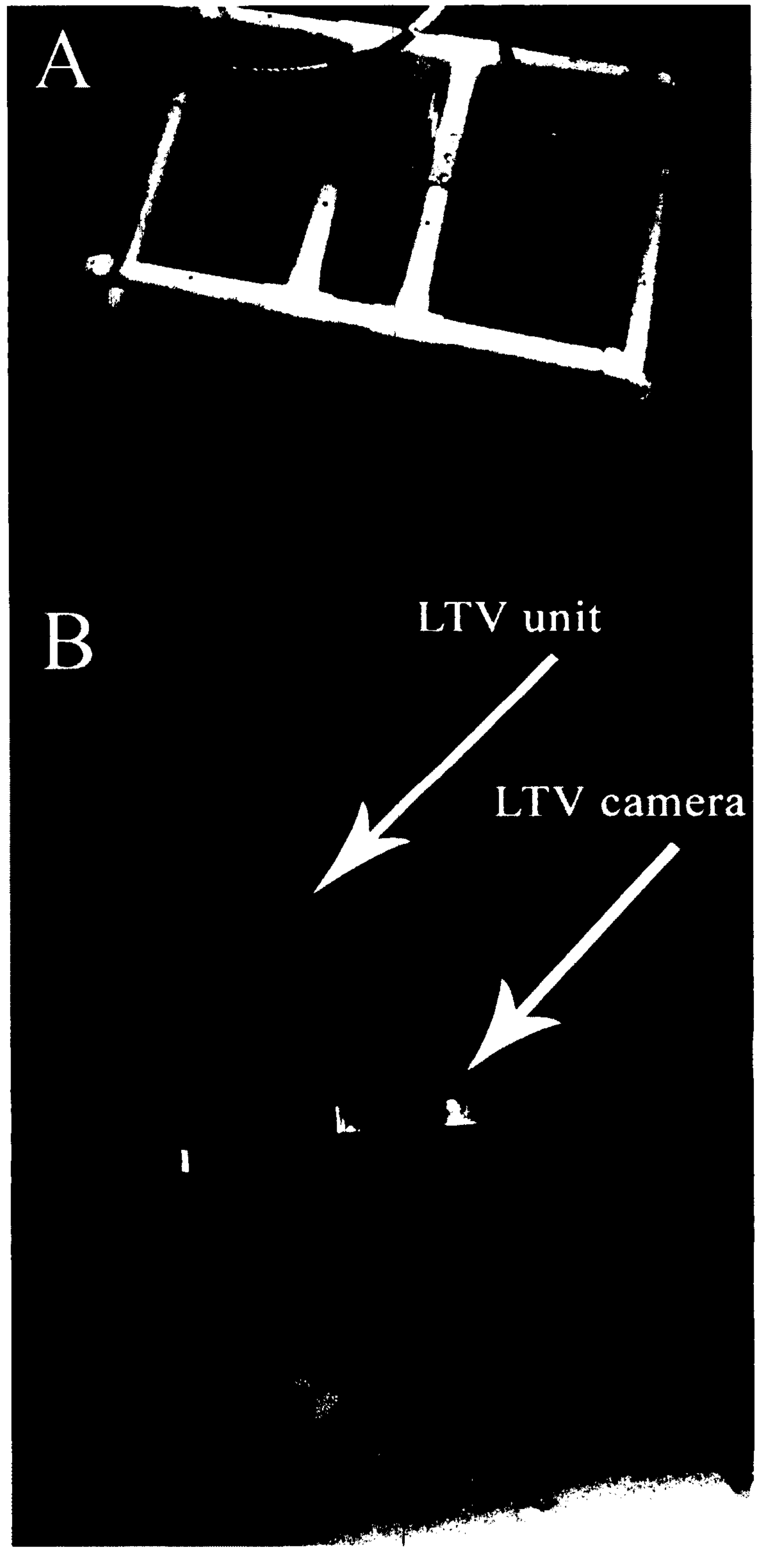

Figure 2.1. A) View of the LTV system mounted on a trap, underwater, at the study site. B) Close-up view of the LTV system, which included a camera mounted in an underwater flashlight housing connected to a waterproof housing containing a DVR and batteries.

Lobster behavior was typically observed from 0900 hours through 2000 hours during each day of the trial. Observations of lobster interactions were made easier by replacing the trap lid with transparent plexiglass so a viewer could more readily observe lobsters inside the kitchen and parlor (Fig. 2.2). The DVR was programmed to record videos at a rate of 5 frames/second.

Both standard and ventless traps were used for the LTV analyses so comparisons could be made between the behaviors of lobsters interacting with both trap types. The traps were deployed at low, medium, and high densities in order to determine how changes in lobster abundance might influence gear saturation in both standard and ventless traps.

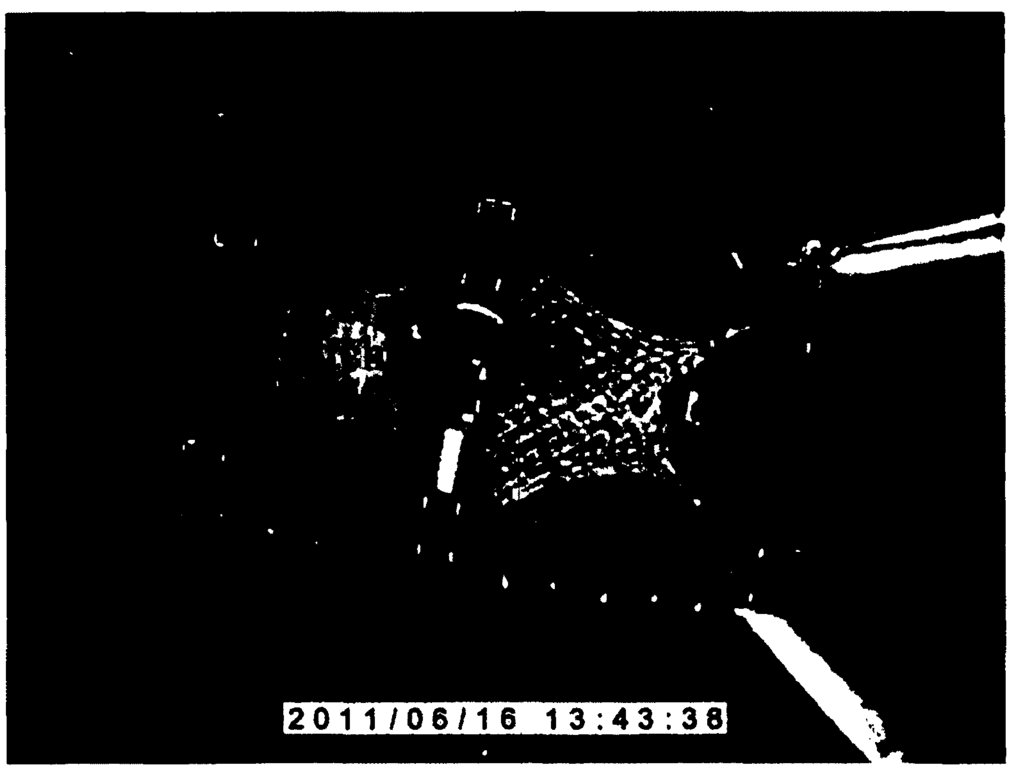

Figure 2.2. Time-stamped single frame of LTV footage. Displayed is the construction of a standard lobster trap, highlighting the kitchen, parlor, entrance head, escape vent, and lobsters in the surrounding field of view. The ventless trap LTV system lacked an escape vent.

Data analysis

To elucidate factors influencing trap saturation, LTV footage was used to quantify the following for each hour the trap was fished: 1) the number of lobsters surrounding the trap; 2) the number of entries into the trap and; 3) the number of lobsters that escaped from the trap. These parameters were assessed for each day of the trial, with every trial consisting of at least two days. No data were obtained during the night, as rate of trap entry does not differ between day and night (Jury *et al.*, 2001). Lobsters were monitored in the surrounding view to determine if they either left the field of view or entered the trap. For lobsters that left the area surrounding the trap and proceeded to enter the trap, they continued to be observed inside the trap to see if they would either enter the parlor (and, in the case of standard traps, exit through the escape vent) or leave the trap via the kitchen entrance. When lobsters left the field of view, they were no longer observed and could have very well returned to the field of view later in the video. Lobsters were unlabeled, so this is merely speculation. After tracking the number of lobsters, rates of entry were calculated using linear regression analyses to determine how these rates might vary over time in standard and ventless traps. Because videos were not recorded over night, the beginning of saturation (between 16 and 24 hours; Chapter 1 Results) was not filmed and segmented linear regression analysis was thus not used.

One goal of this study was to determine the extent to which lobsters were inhibited from entering by other lobsters and, therefore, possibly causing saturation as the trap filled with lobsters. To address this question, we quantified the number of entries and "half-entries" under different circumstances and compared them on Day 1 versus Day 2. Half-entries, as described by Jury *et al.* (2001), were defined as any entry that resulted in lobsters making contact with the mesh funnel of the kitchen entrance, but not fully entering the kitchen. Half-entries, full entries, and escapes were quantified for both standard and ventless traps in order to determine how each parameter changed between Day 1 and Day 2. Trials (n = 3) were performed both at low densities (0.05 lobsters/m^2; n=1) and high densities (> 0.05 lobsters/m^2; n=2). After pooling all of the data into three groups - half-entries, entries, and escapes - we performed Wilcoxon matched nonparametric tests to determine if significant differences existed between Days 1 and 2.

While quantifying entries and escapes, observations were made to determine what prevented lobsters from fully entering traps. Types of deterrents included the following: 1) disturbance by approaching lobsters ("outside lobster"), territoriality exhibited by lobsters already inside the trap ("inside lobster"), current-induced movement of bait bag ("bait bag"), and loss of interest ("unknown"). Deterrents were classified as "unknown" if lobsters approached the trap, oftentimes making contact with it, but left without the influence of any obvious external disturbance. Unlike with the remaining deterrents, "unknown" lobsters rarely exhibited an avoidance response (i.e. tail-flipping) before leaving the field of view.

Results

Movement in and around traps standard and ventless traps

The number of surrounding lobsters, or lobsters within the field of view, were tracked each hour and then compared to the number of entries and escapes. These analyses were performed at both low and high lobster densities. At low densities, there were fewer lobsters observed in the area around both trap types on Day 2 compared to

Day 1 (Fig. 2.3A). However, there were clear differences between the two types of traps. First, more lobsters were entering, escaping and surrounding standard traps in comparison to ventless traps throughout the trial. Similar trends and differences between trap types were observed at when the lobster density was higher, except for the fact that entry rate was similar in both trap types under high-density conditions (Figs. 2.3B & 2.4).

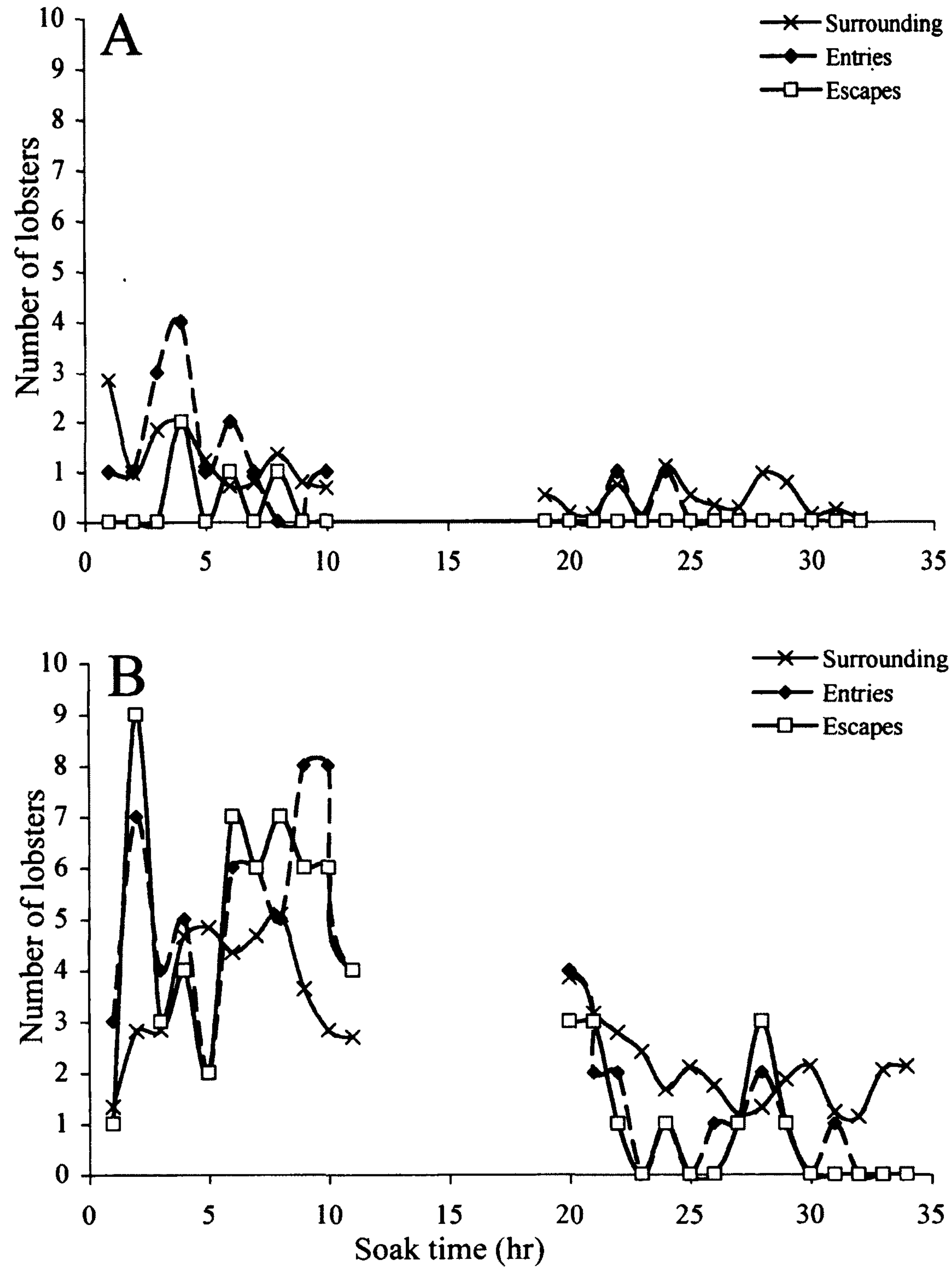

Figure 2.3. A) The number of lobsters surrounding, entering, and escaping ventless traps at a low lobster density (0.024 lobsters/m^2) on Day 1 (hours 1-10) and on Day 2 (hours 19-32). B) Comparable data for a standard trap on Day 1 (1-11) and on Day 2 (20-34). In both traps (n = 1/trap type), there was a reduction in all the parameters on Day 2 compared to Day 1.

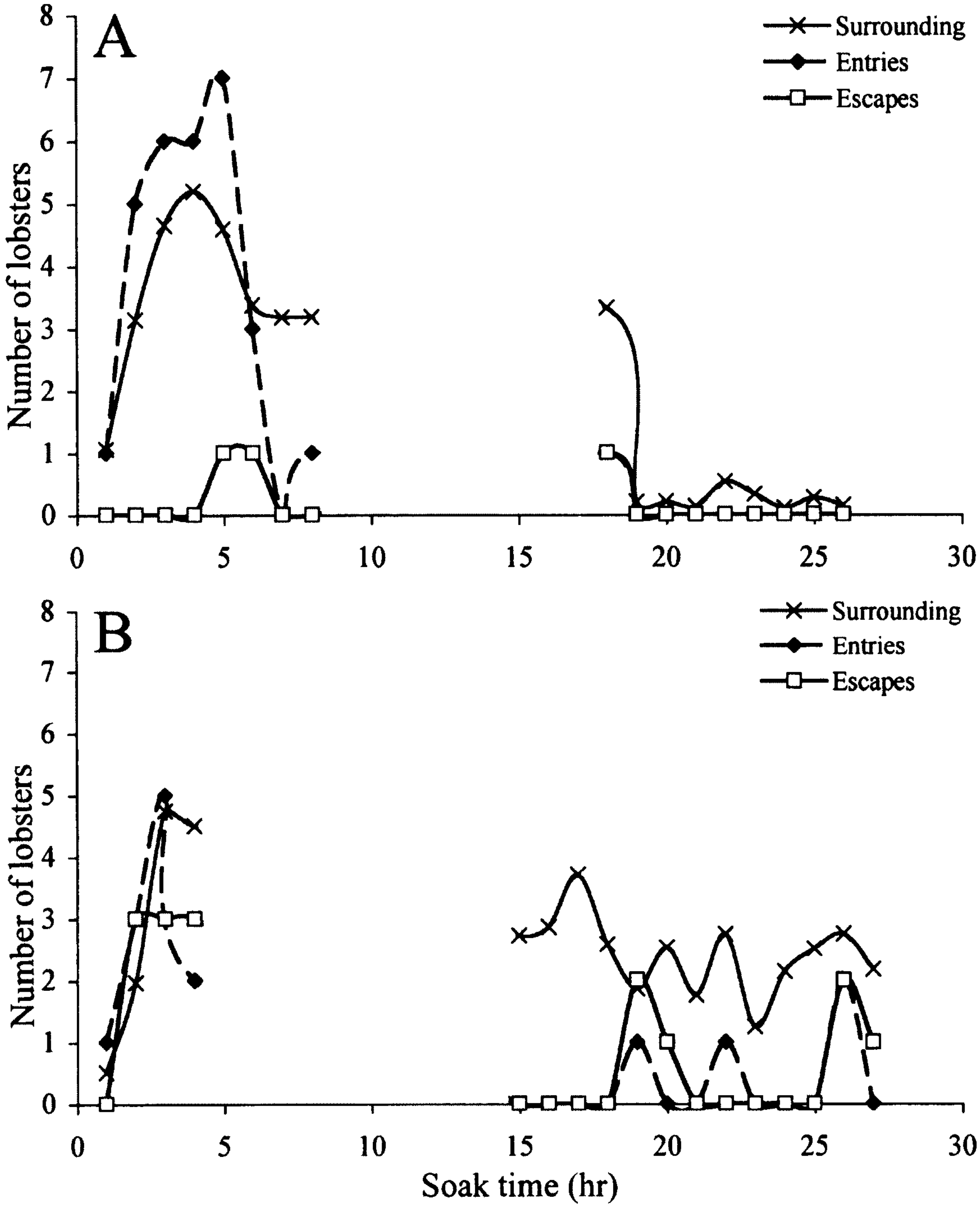

Figure 2.4. A) The number of lobsters surrounding, entering, and escaping a ventless trap at a high lobster density (0.16 lobsters/m^2), on Day 1 (hours 1-8) and Day 2 (hours 18-30). B) Similar data for a standard trap on Day 1 (1-4) and on Day 2 (15-27).

Accumulated entries and escapes

Another way to compare ventless with standard traps, and to address possible mechanisms underlying trap saturation, is to compare accumulated entries, escapes and catch. At low densities (Fig. 2.5), lobsters initially entered standard traps much faster (approximately 5 lobsters/hr) than ventless traps (1.5 lobsters/hr). However, lobsters also escaped from standard traps much faster than ventless traps (5 lobsters/hr, vs. 0.5 lobsters/hr), so the net catch in standard traps was negligible in comparison to the ventless traps. In the standard trap, for example, there was a net catch of approximately three lobsters, whereas the ventless trap caught about 11 lobsters. The same trend was evident on the second day, but both entry and escape rates were much lower than Day 1 and these dynamics are what lead to trap saturation. Similar trends were observed in ventless and standard traps at higher lobster densities (Fig. 2.6). However, at higher densities the entry rate into the ventless traps exceeded the entry rate into standard traps. Note how, as seen at a low density of lobsters, the entry and escape rates in standard traps are equivalent during the first day, in contrast to the ventless traps. Figure 2.7 summarizes all standard traps (n = 3) and ventless traps (n = 3).

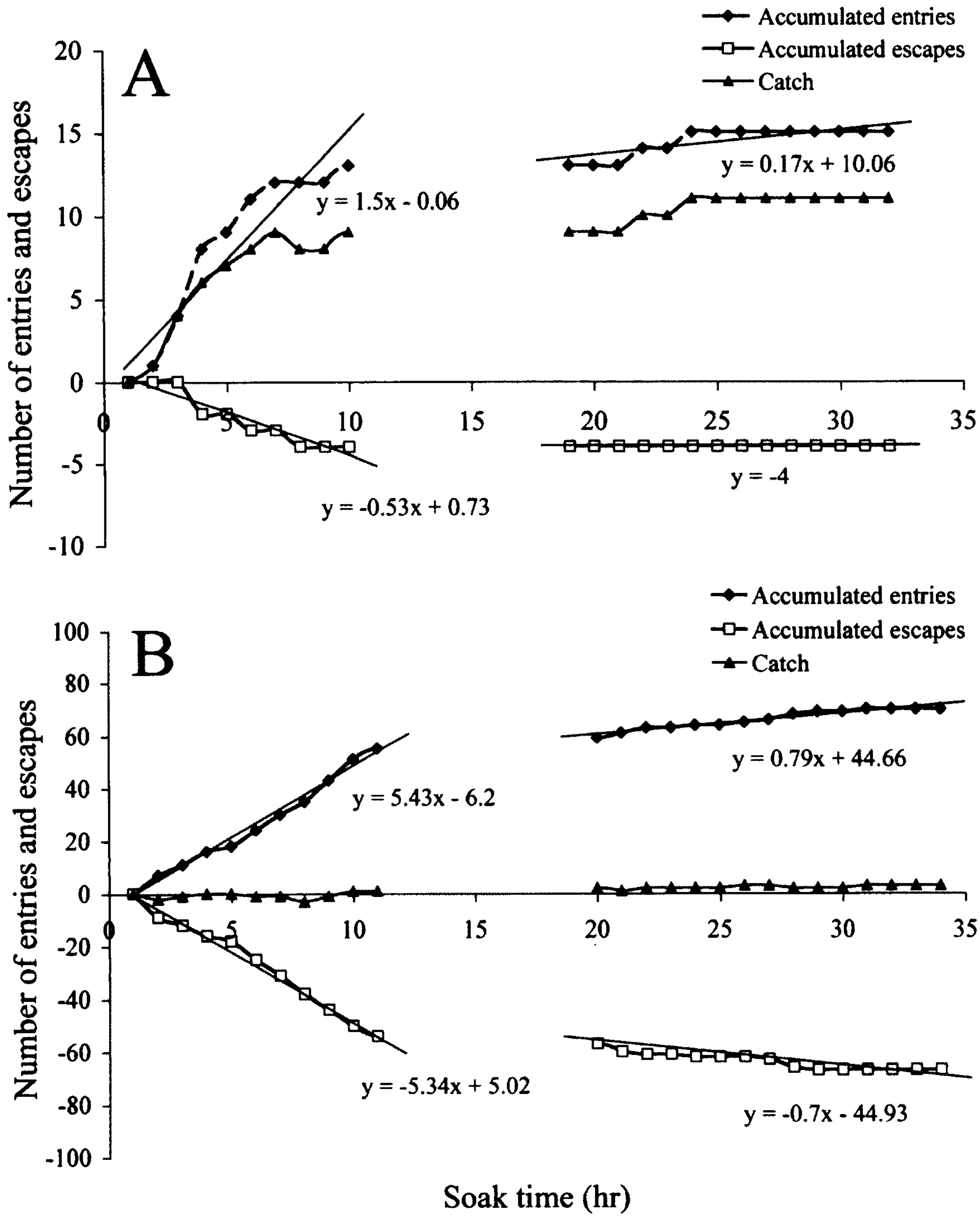

Figure 2.5. Accumulated entries and escapes at a low lobster density (0.024 lobsters/m^2) for a ventless trap (A) and a standard trap (B). Note that the Y-axis is different between A and B.

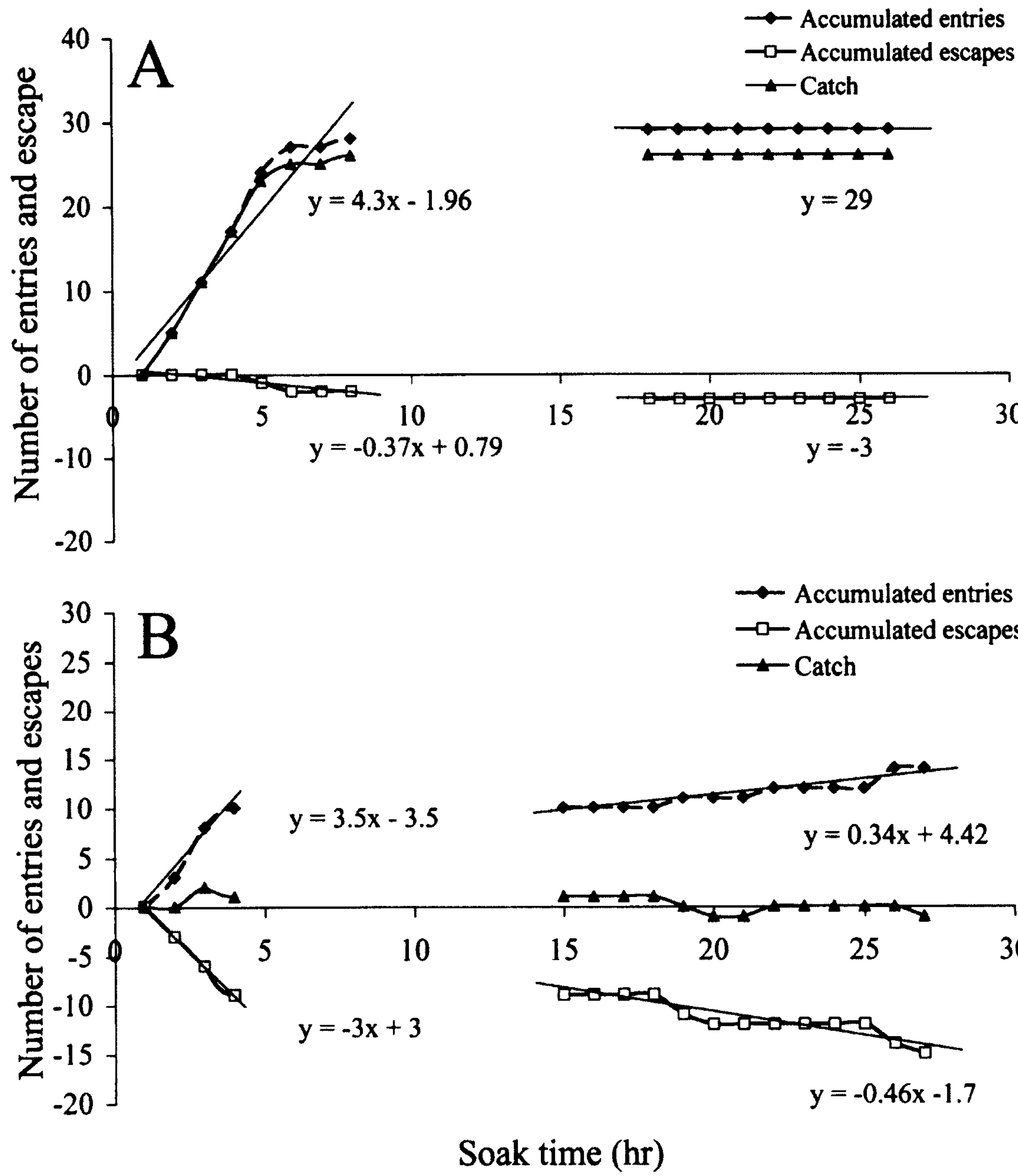

Figure 2.6. Accumulated entries and escapes at a high density of lobsters (0.16 lobsters/m^2) for a ventless trap (A) and standard trap (B).

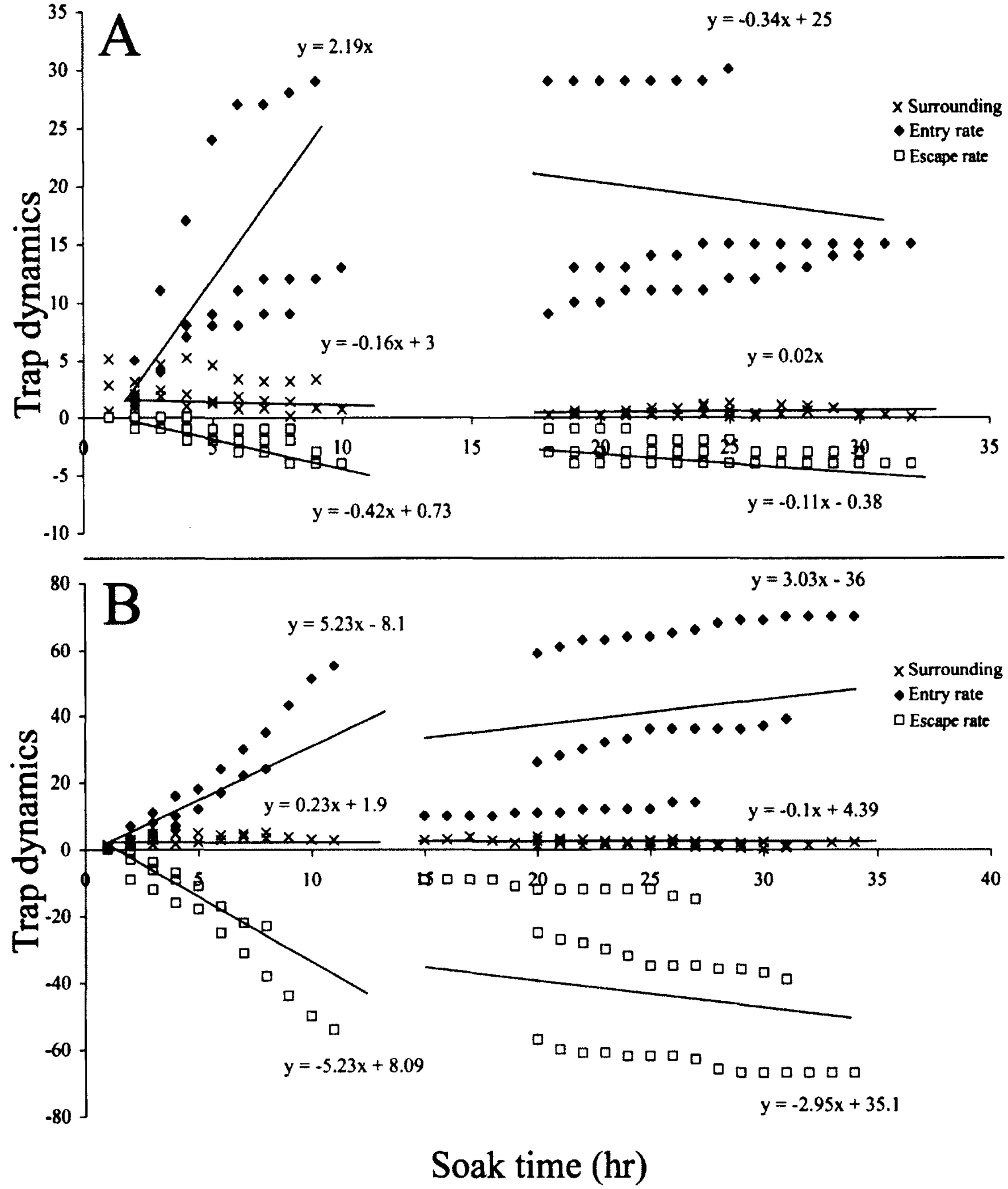

Figure 2.7. Number of surrounding lobsters, entry rate, and escape rate of A) ventless traps (n = 3) and B) standard traps (n = 3). Symbols are provided for each trial and the regression lines are averages of the three trials.

Comparison of half-entries on days 1 and 2 of soak period

There was not a significant reduction in the number half-entries, full entries, and escapes into the ventless trap on Day 2 relative to Day 1 (Fig. 2.8A; P-value = 0.2500, Wilcoxon matched nonparametric test), as observed in the standard trap (Fig. 2.8B; P-value = 0.2500, Wilcoxon matched nonparametric test).

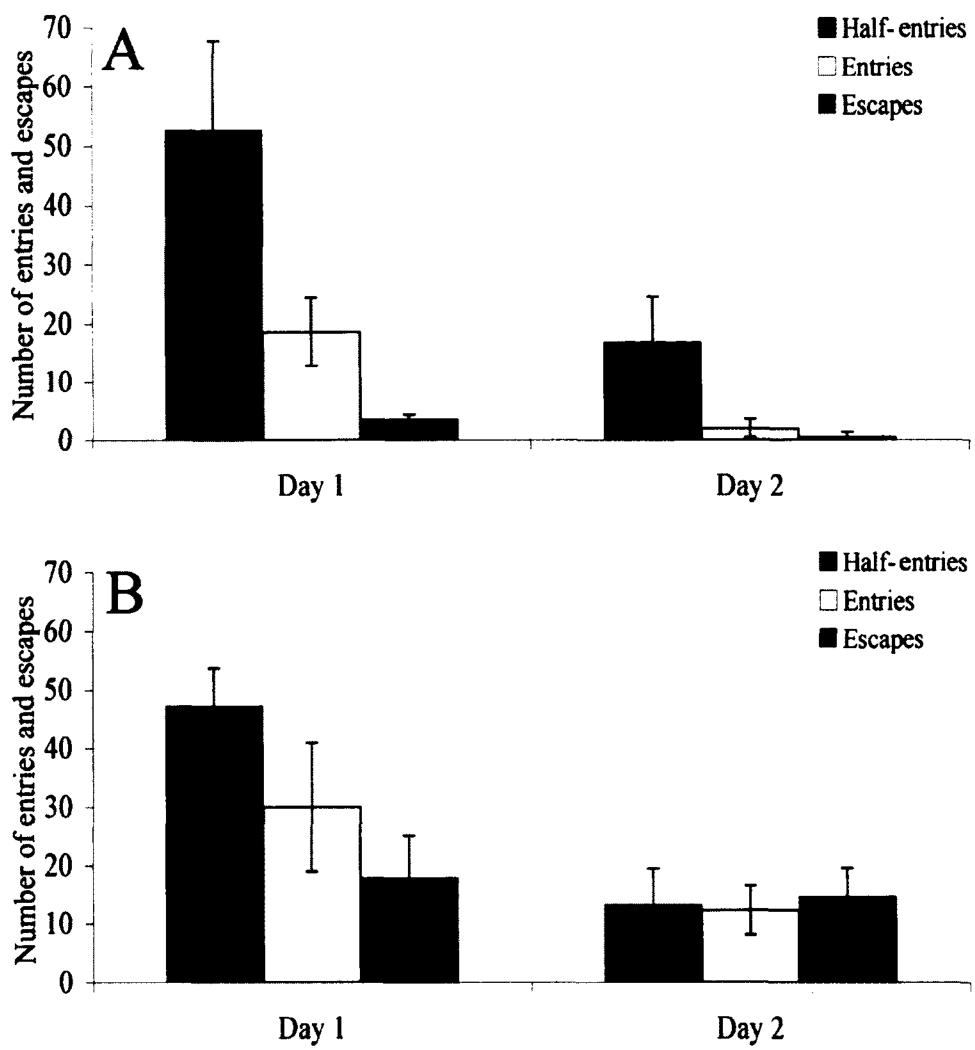

Figure 2.8. The average number of half-entries, entries, and escapes at a low density (0.024 lobsters/m^2) of lobsters for a ventless trap (A) and a standard traps (B). Even though there is a noticeable reduction in half-entries on Day 2 compared to Day 1, the difference is not significant.

The types of deterrents responsible for half-entries are presented in Fig. 2.9, noting that half-entries occurred predominantly due to loss of interest ("unknown") and intimidation by approaching lobsters ("outside lobster").

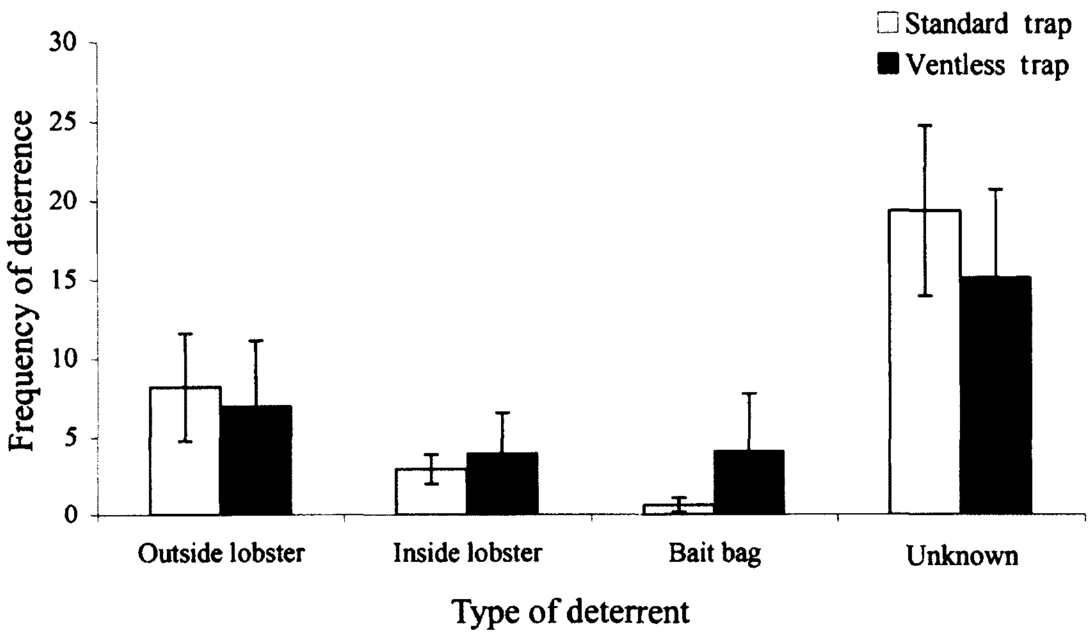

Figure 2.9. Frequency of deterrents per trial (± SEM), averaged between low and high density. Most half-entries resulted from apathy ("other") and deterrence by outside lobsters.

Discussion

This study provided insight into the underlying mechanisms that might cause ventless and standard lobster traps to saturate. Using the LTV system, it was possible to observe lobsters in, and around, standard and ventless traps while they were fishing for 2 days. Based on our observations, trap saturation was the result of different causes for each type of trap. For ventless traps, which saturated after 16-24 hours, a major factor appears to be a reduction in the density of lobsters in the vicinity of the trap. This decrease most likely occurred because most of the lobsters in the area fished by the trap had been captured and retained inside the trap, specifically inside the parlor. Saturation of the standard trap, on the other hand, was largely due to the clear balance between the rate of entry and rate of escape during almost all hours of the soak.

Agonistic encounters

Behavioral interactions between lobsters and their conspecifics are linked to reduction in trap catch (Richards *et al.*, 1983; Miller, 1990, Frusher & Hoenig, 2001; Barber & Cobb, 2009). Similar interactions were observed in the present study. Many experiments have confirmed that American lobsters are aggressive in their inter- and intraspecific interactions (Tamm & Cobb, 1978; Rutishauser *et al.*, 2004; Steneck *et al.*, Williams *et al.*, 2006, Williams *et al.*, 2009). Agonistic behavior is, therefore, common amongst lobsters congregating in and near lobster traps, as is the case with other decapods, including the rock lobster *Jasus edwardsii* and mud crab *Scylla serrata* (Robertson, 1989; Jury *et al.*, 2001; Ihde & Frusher, 2006). In all of these studies, antagonistic encounters appeared to contribute to reduced trap entry, a factor believed to cause trap saturation (Miller, 1979).

One way to test the hypothesis that traps saturate because lobsters inside the trap prevent others from entering is to "pre-stock" traps and to then determine if this reduces subsequent catch. In 1983, Richards *et al.* did this and their study illustrated that pre-stocking traps with lobsters inhibits the ingress of lobsters and some crab species. Recently, Watson and Jury (in press) demonstrated that pre-stocking does limit rate of entry, but it does not reduce the total catch (if the total catch includes the stocked lobster) in standard traps. In my study, I attempted to quantify influence of lobsters inside the trap on entries by determining if there was a relationship between lobster-lobster interactions and the number of times lobsters entered halfway. Interestingly, in this study, lobsters inside the trap were not the dominant cause of half-entries. Rather, lobsters outside of the trap accounted for 25% of all half-entries (Fig. 2.9). When lobsters approached the trap, other encroaching lobsters often deterred them by lunging or chasing them away from the trap entrance. This type of territoriality was observed in the presence of standard and ventless traps, which limited the frequency of successful entries into each trap. Therefore, even when there were a few lobsters inside the kitchen, entry rates were more influenced by interactions outside the trap. Furthermore, because most lobsters in ventless traps accumulated in the parlor, rather than the kitchen, it is unlikely that they influenced subsequent trap entries. Thus, these data, while consistent with previous studies, indicate that behavioral interactions amongst lobsters inside the trap and outside the trap are probably not the primary cause of trap saturation. We hypothesize that saturation of ventless traps was instead largely due to lobsters being captured and removed from surrounding area.

For ventless traps, the decline in lobsters outside of the trap was negatively correlated with lobsters inside the trap. Because the lobsters were unlabeled, it was not possible to track the movement of individual lobsters. It can, therefore, not be concluded that lobsters in the surrounding field of view at the point of deployment were in fact the same lobsters to have been caught later in the trial. However, there still remains a clear relationship between increasing CPUE of ventless traps and decreasing surrounding lobster activity. Similar to catch in ventless traps, the area around fishing standard traps showed a reduction in the number of outside lobsters. Because most of the lobsters (>90%) were sublegal-sized, they were able to exit through the standard trap escape vents as acknowledged in previous studies (Nulk, 1978; Saila *et al.*, 2002).

Entry and escape rates

The rate of lobster entries and escapes varied between the two types of traps. For standard traps, lobsters entered and escaped at approximately the same rates, both at high and low densities (Figs. 2.5 - 2.6). Thus, the net catch was low. In standard traps when a lobster entered via the kitchen entrance, it would either escape back out the entrance or move into the parlor. As observed by Karnofsky and Price (1989), lobsters would often leave the parlor instantly upon entering it (< 2 minutes). Because entry and escape rates were in equilibrium almost immediately, standard traps were said to saturate four hours after deployment. Again, it is important to remember, most of the lobsters in this area were sublegal and therefore they could easily escape through the mesh or the escape vent in the parlor. Unlike standard traps, ventless traps did not experience equal entry and escape rates, since lobsters could not exit the parlor through the escape vent. Even though lobsters were unable to exit through the parlor, few lobsters escaped through the kitchen entrance as documented for standard traps by Jury *et al.* (2001). Therefore, even though lobsters were capable of exiting the ventless traps through the entrances in the kitchen, overall they escaped from ventless traps at a much slower rate than they escaped from standard traps. For example, at a low density of 0.024 ± 0.007 lobsters/m^2, lobsters initially entered ventless traps at a rate of approximately 1.5 lobsters/hr and escaped at a rate of 0.53 lobsters/hr. This would yield a catch rate of approximately 1 lobster/hr, which is similar to the calculation of 0.8 lobsters/hr that the saturation data yielded in Chapter One. Standard traps fishing in the same density experienced an entry rate of 5.43 lobsters/hour and an escape rate of 5.33 lobsters/hour, so they only accumulated at a rate of approximately 0.1 lobsters/hr. After having fished for 15 to 18 hours, the rates of entries and escapes were reduced in both types of traps. While the standard traps continued to be in a state of equilibrium (entry rate = escape rate), ventless traps also reached a plateau where the rate of entry was close to the rate of escape. Most likely, based on the catch data presented in Chapter One, this balance continued for soak times > 48 hours as well.

If ventless traps accumulate lobsters at a rate of about 1 lobster/hr, then after 24 hours they would contain 24 lobsters. At a density of 0.024 lobsters/m^2, there would be 24 lobsters in an area of $10{,}000m^2$, or an area that is 100m x 100m. In 2009, Watson *et al.* estimated that the area of bait attraction for a lobster trap was $380m^2$, and the trapping area to be $2{,}600m^2$, for a 24-hour soak. Therefore, it certainly seems possible that, after approximately 24 hours, a ventless trap fishing in an area with a low density of lobsters, could catch most of them in 24 hrs. This in term would lead to less animals surrounding and entering the trap, and eating the bait. More importantly, as a result, the traps would saturate. This hypothesis is further supported by the following additional data: 1) after 24 hours ventless traps have about 40-50% of their bait left and thus bait deterioration is not a major factor in trap saturation, at least at intervals of < 48 hours; 2) after 24-72 hours ventless traps have more bait left than standard traps, most likely due to lobsters escaping and entering again (Chapter One, Results). This suggests that most of the lobsters have been captured and, therefore, there are fewer left to enter and consume the bait and; 3) as densities increase, traps still saturate, but at higher values (Chapter 1, Results). If they were saturating because the traps were filling and lobsters inside the trap were keeping those outside from entering, then it seems likely that traps would saturate at some fixed value, regardless of lobster density. Instead, we propose, that they continue to fish until they have removed most of the catchable lobsters in the vicinity of the trap, so catch reaches a plateau even though there is still room in the trap, and bait in the bag.

CONCLUSIONS

This study achieved its goal of investigating lobster trap saturation and factors responsible for its onset. In the first chapter, ventless and standard traps were fished in pairs to learn the relationship between catch and lobster density. Not knowing when or how saturation would affect the catch data, trap pairs were fished for a range of soak times, spanning from 2 hours to 96 hours, in order to determine the point of saturation. After two seasons, it was concluded that ventless traps saturate between 16 and 24 hours and standard traps saturate within four hours. It was further deduced that ventless trap saturation is positively correlated with lobster density and, therefore, better reflects estimated lobster abundance. For example, a lobster density of 0.114 ± 0.028 lobsters/m^2 yields more CPUE than that of a lower density demonstrating that ventless traps do not saturate at the same catch level. Instead, ventless traps saturate as a function of lobster abundance.

In the second chapter, mechanisms underlying trap saturation were explored using the LTV system. This autonomous apparatus made it possible to observe interacting lobsters in and around fishing traps. Contrary to initial hypotheses, trap saturation was not significantly linked to behavioral interaction. While it was not uncommon to observe lobsters fighting in the presence of a trap, as documented in past studies (Richards *et al.*, 1983; Karnofsky & Price, 1989; Jury *et al.*, 2001), aggressive encounters did not seem to be the major contributor to saturation. Instead, trap saturation was correlated with reduced entry rate over time. In the case of ventless traps, most lobsters entering the trap parlor were unable to leave it due to the lack of escape vent. As more lobsters entered the trap, more lobsters were removed from the area surrounding the trap. With fewer lobsters around the trap, there were fewer lobsters to enter, thus, entry rate was reduced. The present study illustrated that trap saturation can be induced by two factors, fishing out all lobsters in the trapping area and depleting the bait source.

These two contributors of trap saturation did not directly cause traps to saturate. They altered the trap-based system in such a way that catch rate changed over time. For ventless traps, lobsters entered the trap faster than they could escape because there was no escape vent. Standard traps, on the other hand, entered a state of equilibrium almost immediately upon deployment. Since an escape vents were present, lobsters could easily enter and leave the traps at will. Trap saturation is a complex concept that, unless fully understood, could have negative implications on stock assessment measures. With the help of this study and related ones, managers will be better equipped to standardize sampling programs and to maximize fishing efforts.

FUTURE DIRECTIONS

Trap saturation

Future investigations should further explore ventless trap saturation and how additional trap modifications might influence its selectivity. In a previous study, Zhou and Shirley (1997) compared two types of crab pots, one crab pot design containing a one-way entrance and the other not. Adding the one-way opening increased the crab pot selectivity in that the pot caught more legal-sized males, while releasing more females and sublegal males. Applying one-way kitchen entrances to ventless traps would presumably increase the rate of saturation in that lobsters would no longer be able to escape through the kitchen head. They would have to either stay in the kitchen or relocate to the parlor, being unable to escape from either compartment. Hypothetically, the one-way opening would be less discriminate in terms of size selectivity. The modified trap design might, therefore, provide an even more accurate estimate of size frequency composition than traditional ventless traps.

Lobster trap video

In this study and in prior ones (Jury *et al.*, 2001), the LTV system has proven to be a valuable tool for studying *in situ* lobster behavior. This technology could, thus, be incorporated into studies assessing the relationship between trap saturation and trap modification (see above). The LTV system should also be used to investigate behavior characteristic of individual lobsters. Even though animal behavior can be variable, specifically among lobsters, previous *in vitro* studies suggest that some lobsters are "untrappable" and might avoid entering traps (Karnofsky & Price, 1989). Labeling and monitoring individual lobster behavior would garner insight into the lobster social structure.

Tracking individual lobsters would also prove useful when testing satiation as a possible cause of trap saturation. Because there were fewer lobsters inside or around standard traps on Day 2 compared to Day 1 (Figs. 2.3 & 2.4) and still approximately 20% bait remaining inside the bait bag, this suggests that the lobsters were no longer hungry. This could be due, in part, to a reduction in bait quality. When a lobster trap is deployed, its area of bait influence is approximately 11 meters depending on the size and quality of bait used (Watson *et al.*, 2009). As bait is consumed over time, its effect would presumably decrease proportionally to its disintegration. Further studies need to be conducted to further explore the relationship between bait quality, soak time, and catch in standard traps. For example, marking individual lobsters either *in situ* or inside a laboratory setting and then monitoring their level of feeding activity in response to a baited standard trap would potentially provide insight into lobster satiation and its implications on trap saturation.

LIST OF REFERENCES

Addison JT. 1995. Influence of behavioural interactions on lobster distribution and abundance as inferred from pot-caught samples. ICES Marine Science Symposium 199: 294-300.

Addison JT, Bannister RC. 1998. Quantifying potential impacts of behavioral factors on crustacean stock monitoring and assessment: modeling and experimental approaches. In: Jamieson, G. Campbell, A. (eds) Proceedings of the North Pacific Symposium on Invertebrates Stock Assessment and Management. Canadian Special Publications of Fisheries and Aquatic Sciences: 163-177.

Archdale MV, Anasco CP, Kawamura Y, Tomiki S. 2007. Effect of two collapsible pot designs on escape rate and behavior of the invasive swimming crabs *Charybdis japonica* and *Portunus pelagicus*. Fisheries Research 85: 202-209.

ASMFC (Atlantic States Marine Fisheries Commission). 2012a. American Lobster. Web. 9 June 2012. < http://www.asmfc.org/>

ASMFC (Atlantic States Marine Fisheries Commission). 2012b. Interstate Fisheries Management. Web. 9 June 2012. < http://www.asmfc.org/>

Auster PJ. 1985. Factors affecting catch of American lobster, *Homarus americanus*, in baited traps. University of Connecticut. 51 pp.

Auster PJ. 1986. The utility of computing CPUE at each level of effort in the lobster trap fishery. Northwest Atlantic Fisheries Organization Scientific Council Studies 10: 53-56.

Barber JS, Cobb JS. 2009. Qualitative observations of Dungeness crabs, *Cancer magister*, in and around traps: evidence of resource guarding and clustering. Marine and Freshwater Behaviour and Physiology 42: 135-146.

Caddy JF. 2003. Current usage of fisheries indicators and reference points, and their potential application to management of fisheries for marine invertebrates. Canadian Journal of Fisheries and Aquatic Sciences 61: 1307-1324.

Chen Y, Sherman S, Wilson C, Sowles J, Kanaiwa M. 2006. A comparison of two fishery-independent survey programs used to define the population structure of

American lobster (*Homarus americanus*) in the Gulf of Maine. Fishery Bulletin 104: 247-255.

Cooper RA, Uzmann JR. 1971. Migration and growth of deep-sea lobsters, *Homarus americanus*. Science 171: 288-290.

Courchene B, Stokesbury KDE. 2011. Comparison of vented and ventless trap catches of American lobster with scuba transect surveys. Journal of Shellfish Research 30: 389-401.

Crossin GT, Al-Ayoub SA, Jury SH, Howell WH, Watson WH III. 1998. Behavioral thermoregulation in the American lobster *Homarus americanus*. Journal of Experimental Biology 201: 365-374.

DMR (Maine Department of Marine Resources). 2001. Coastal Fishery Research Priorities: American Lobster (*Homarus americanus*). Web.10 June 2012. http://www.maine.gov/dmr/research/lobster.htm

DMR (Maine Department of Marine Resources). 2012a. 2012 Maine Fishermen's Forum Landings Handout. Web. 9 June 2012. http://www.maine.gov/dmr/commercialfishing/recentlandings.htm

DMR (Maine Department of Marine Resources). 2012b. Maine Department of Marine Resources Coastal Fishery Research Priorities Lobster (*Homarus americanus*). Web.9 June 2012. http://www.maine.gov/dmr/research/priorities10/lobster/lobstersummary.pdf

DMR (Maine Department of Marine Resources). 2011. Maine Ventless Lobster Trap Study. Web.12 June 2012. http://www.maine.gov/dmr/rm/lobster/ventless/

Drinkwater KF, Tremblay MJ, Comeau M. 2006. The influence of wind and temperature on the catch rate of the American lobster (*Homarus americanus*) during spring fisheries off eastern Canada. Fisheries Oceanography 15: 150-165.

Estrella BT, Glenn RP. 2006. Lobster trap escape vent selectivity. Massachusetts Division of Marine Fisheries Technical Report TR-27.

Estrella BT, Morrissey TD. 1997. Seasonal movement of offshore American lobster, *Homarus americanus*, tagged along the eastern shore of Cape Cod, Massachusetts. Fishery Bulletin 95: 466-476.

Fogarty MJ, Addison JT. 1997. Modelling capture processes in individual traps: entry, escapement and soak time. ICES Journal of Marine Science 54: 193-205.

Frusher SD, Hoenig JM. 2001. Impact of lobster size on selectivity of traps for southern rock lobsters (*Jasus edwardsii*). Canadian Journal of Fisheries and Aquatic Sciences 58: 2482-2489.

Geraldi NR, Wahle RA, Dunnington M. 2009. Habitat effects on American lobster (*Homarus americanus*) movement and density: insights from georeferenced trap arrays, seabed mapping, and tagging. Canadian Journal of Fisheries and Aquatic Sciences 66: 460-470.

Glenn RP, Pugh TL, Casoni D, Carver J. 2007. Random stratified ventless trap survey design for pilot study in Massachusetts Bay. Northeast Consortium Final Report.

Goldstein JS, Watson WH III. 2012. The impact of seasonal movement by ovigerous American lobster (*Homarus americanus*) on egg development and larval release. Ph.D. Thesis. University of New Hampshire, Durham. 332 pp.

High WL, Beardsley AJ. 1970. Fish behavior studies from an undersea habitat. Commericial Fisheries Review 32: 31-37.

Ihde TF, Frusher SD, Hoenig JM. 2006. Do large rock lobsters inhibit smaller ones from entering traps? A field experiment. Marine and Freshwater Research 57: 665-674.

Jury SH, Howell WH, O'Grady DF, Watson WH III. 2001. Lobster trap video: in situ video surveillance of the behavior of *Homarus americanus* in and around traps. Marine and Freshwater Research 52: 1125-1132.

Jury SH, Kinnison MT, Howell WH, Watson WH III. 1994a. The behavior of lobsters in response to reduced salinity. Journal of Experimental Marine Biology and Ecology 180: 23-37.

Jury SH, Kinnison MT, Howell WH, Watson WH III. 1994b. The effects of reduced salinity on lobster (*Homarus americanus* Milne-Edwards) metabolism: implications for estuarine populations. Journal of Experimental Marine Biology and Ecology 176: 167-185.

Jury SH, Howell WH, Watson WH III. 1995. Lobster movements in response to a hurricane. Marine Ecology Progress Series 119: 305-310.

Jury SH, Watson WH III. 2000. Thermosensitivity of the American lobster, *Homarus americanus*. Biological Bulletin 199: 257-264.

Karnofsky EB, Price HJ. 1989. Behavioral response of lobster *Homarus americanus* to traps. Canadian Journal of Fisheries and Aquatic Sciences 46: 1625-1632.

Lokkeborg S. 1990. Rate of release of potential feeding attractants from natural and artificial bait. Fisheries Research 8: 253-261.

MADMF (Massachusetts Division of Marine Fisheries). 2009. Programs and Projects: Monitoring and Assessment. Web. 10 June 2012. http://www.mass.gov/dfwele/dmf/programsandprojects/hubline/monitoring.htm

Mackie AM, Grant PT, Shelton RG. 1980. The relative efficiencies of natural and artificial baits for the lobster, *Homarus gammarus*: laboratory and field trials. Journal du Conseil 39: 123-129.

Miller RJ. 1979. Saturation of crab traps: reduced entry and escapement. Journal du conseil international pour l'exploration de la mer 38: 338-345.

Miller RJ. 1990. Effective of crab and lobster traps. Canadian Journal of Fisheries and Aquatic Sciences 47: 1228-1250.

Miller RJ. 1995. Catchability coefficients for American lobster (*Homarus americanus*). ICES Marine Science Symposium 199: 349-356.

Miller RJ, Rodger R. 1996. Soak times and fishing strategy for American lobster. Fisheries Research 26: 199-205.

Munro JL. 1974. The mode of operation of Antillean fish traps and the relationships between ingress, escapement, catch and soak. Journal du conseil international pour l'exploration de la mer 35: 337-350.

NH Fish and Game. ME/NH Inshore Trawl Survey. Web. 18 July 2012. http://www.wildlife.state.nh.us/marine/research.html

NOAA Fisheries Service: Sustainable Fisheries Division 2012. Fishery Management Plans American Lobster. Web. 9 June 2012. http://www.nero.noaa.gov/sfd/lobster/

NOAA FishWatch 2012. Harvesting American Lobster. Web. 12 June 2012. http://www.fishwatch.gov/seafood_profiles/species/lobster/species_pages/american_lobster.htm

Nulk VE. 1978. The effects of different escape vents on the selectivity of lobster traps. Marine Fisheries Review 40: 50-60.

O'Neill DJ, Cobb JS. 1979. Some factors influencing the outcome of shelter competition in lobsters (*Homarus americanus*). Marine Behavior Physiology 6: 33-45.

Ovegard M, Konigson S, Persson A, Lunneryd SG. 2011. Size selective capture of Atlantic cod (*Gadus morhua*) in floating pots. Fisheries Research 107: 239-244.

Poeschel CL. 2002. A pilot study to test ventless traps as a means to quantify populations of the American lobster (*Homarus americanus*) in Maine. Master's Thesis University of Maine. 46 pp.

Prchalová M, Mrkvicka T, Peterka J, Cech M, Berec L, Kubecka J. 2011. A model of gillnet catch in relation to the catchable biomass, saturation, soak time and sampling period. Fisheries Research 107: 201-209.

Pezzack DS, Duggan DR. 1986. Evidence of migration and homing of lobsters (*Homarus americanus*) on the Scotian Shelf. Canadian Journal of Fisheries and Aquatic Sciences 43: 2206-2211.

Pickering T, Williams J, Apaloo J. 2010. Catch variation among traps in an American lobster (*Homarus americanu*) trawl. Fisheries Research 106: 555-559.

Richards RA, Cobb JS. 1986. Competition for shelter between lobsters (*Homarus americanus*) and Jonah crabs (*Cancer borealis*): effects of relative size. Canadian Journal of Fisheries and Aquatic Sciences 43: 2250-2255.

Richards RA, Cobb JS, Fogarty MJ. 1983. Effects of behavioral interactions on the catchability of American lobster, *Homarus americanus*, and two species of Cancer crab. Fishery Bulletin 81: 51-60.

Robertson WD. 1989. Factors affecting catches of the crab Scylla-serrata (Forskål) (Decapoda: Portunidae) in baited traps: Soak time, time of day and accessibility of the bait. Estuarine, coastal and shelf science 29: 161-170.

Rutishauser RL, Basu AC, Cromarty SI, Kravitz EA. 2004. Long-term consequences of agonistic interactions between socially naïve juvenile American lobsters (*Homarus americanus*). Biological Bulletin 207: 183-187.

Saila SB, Nixon SW, Oviatt CA. 2002. Does lobster trap bait influence the Maine inshore trap fishery? North American Journal of Fisheries Management 22: 602-605.

Scheirer K, Chen Y, Wilson CJ. 2004. A comparative study of American lobster fishery sea and port sampling programs in Maine: 1998-2000. Fisheries Research 68: 343-350.

Steneck RS. 2006. Possible demographic consequences of intraspecific shelter competition among American lobsters. Journal of Crustacean Biology 26: 628-638.

Steneck RS, Wilson CJ. 2001. Large-scale and long-term spatial and temporal patterns in demography and landings of the American lobster, *Homarus americanus,* in Maine. Marine and Freshwater Research 52: 1303-1319.

Tamm GR, Cobb JS. 1978. Behavior and the crustacean molt cycle: changes in aggression of *Homarus americanus*. Science 200: 79-81.

Tremblay MJ, Lanteigne M, Mallet M. 1998. Size-specific estimates of lobster catchability in the Baie des Chaleurs based on traps with different entrance ring sizes. Canadian Technical Report of Fisheries and Aquatic Sciences No. 2222.

Tremblay MJ, Smith SJ, Robichaud DA, Lawton P. 2006. The catchability of large American lobsters (*Homarus americanus*) from diving and trapping studies off Grand Manan Island, Canadian Maritimes. Canadian Journal of Fisheries and Aquatic Sciences 63: 1925-1933.

Wahle RA, Steneck RS. 1992. Habitat restrictions in early benthic life-experiments on habitat selection and in situ predation with the American lobster. Journal of Experimental Marine Biology and Ecology 157: 91-114.

Watson WH III, Golet W, Scopel D, Jury SH. 2009. Use of ultrasonic telemetry to determine the area of bait influence and trapping area of American lobster, *Homarus americanus*, traps. New Zealand Journal of Marine and Freshwater Research 43: 411-418.

Watson WH III, Jury SH. In press. The relationship between American lobster catch, entry rate into traps and density. Marine Biology Research.

Watson WH III, Vetrovs A, Howell WH. 1999. Lobster movements in an estuary. Marine Biology 134: 65-75.

Weiss HM, Lozano-Alvarez E, Briones-Fourzán P, Negrete-Soto F. 2006. Using red light with fixed-site video cameras to study the behavior of the spiny lobster, *Panulirus argus*, and associated animals at night and inside their shelters. Marine Technology Society Journal 40: 86-95.

Williams PJ, Floyd TA, Rossong MA. 2006. Agonistic interactions between invasive green crabs, *Carcinus maenas* (Linnaeus), and sub-adult American lobsters, *Homarus americanus* (Milne Edwards). Journal of Experimental Marine Biology and Ecology 329: 281-288.

Williams PJ, MacSween C, Rossong M. 2009. Competition between invasive green crabs (*Carcinus maenas*) and American lobster (*Homarus americanus*). New Zealand Journal of Marine and Freshwater Research 43: 29-33.

van Tamelen PG. 2001. Effect of pot soak time on crab catch in the Bering Sea and Aleutian Islands. Alaska Department of Fish and Game Regional Information Report No. 5J01-18.

Zhou SJ, Shirley TC. 1997. Performance of two red king crab pot designs. Canadian Journal of Fisheries and Aquatic Sciences 54: 1858-1864.